An Expert System Based Aid for Anode Production at an Aluminium Smelter

by

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DECLARATION OF ORIGINALITY

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ABSTRACT

In the smelting of aluminium, a high current is passed between an anode and a cathode across a molten bath of electrolyte. As the anode is consumed in the electrolytic process, the manufacture of anodes represents a high operational cost. Better control of the anode production process could lead to a reduction in the variability of anode qualities, improved anode performance and a resulting longer anode life with a concomitant reduction in operational costs.

The production process of anodes is controlled by operators through a Supervisory Control and Data Acquisition (SCADA) system that continuously polls the front line program logic control of the anode plant. Information relating to potential problems or causes of existing problems is available, which an experienced operator can obtain by querying the SCADA system. As there is too much data for the operator to assimilate to properly control the process, the operator tends to rely on the control system itself to control the process within its own limitations, since more pressing problems usually divert him from this fine tuning task. Thus, anodes are produced that generally meet specification, but with some degree of variability.

The work presented in this thesis addresses the use of artificial intelligence techniques to develop a decision support system for use by the anode plant operators. Research focused on the following issues:

- identification of the process parameters that critically affect an anode's properties;
- determination of the problems, and their causes, that affect those process parameters;
- determination of the most appropriate way to present information to the operator;
- development of the required software;
- determination of the best methods, in terms of speed and PC memory, of exchanging data with SCADA;
- development of a robust application that runs continuously, without failure, for a ten day production run.

The developed application, based on *Level5 Object* software, continuously interrogates the process control system and provides on-line analysis to operators of ten process variables identified as critically affecting anode properties. For each process variable, are displayed a triplet of statistical process control charts and messages advising of trends, potential problems and possible causes of those problems. Utilising hypertext, the operator can view and print out a Standard Operating Procedure to rectify said problem. Properly used, the monitor provides the operator with a high level tool to enable anodes to be made to a consistent quality within tight process limits.

The research has established the necessary techniques to design a system to continuously oversee and monitor a complex production process, to analyse large amounts of data in real time and to provide meaningful and timely information to the operator to enable the application of the necessary corrective action. The developed system has been installed for live monitoring of the process by technical personnel during 1996 and for operator use in 1997.

Two refereed papers have been published and presented at international conferences.

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1. INTRODUCTION

1.1 Historical Context

The control of processes involving machinery of all types has evolved over the past ten years from using electro-mechanical relays to using programmed logic control (PLC) systems utilising solid state devices. Coupling PLC's with computers has resulted in Supervisory, Control and Data Acquisition (SCADA) management systems that can provide a means of observing and controlling a process from a single station.

In the same ten year period, changes in workplace attitudes have moved from the restrictive practices and strict demarcation between different categories of workers that prevailed into the 1980's, to multi-skilling and the single status workforce of the 1990's. A multi-skilled person operates and maintains equipment and has skills in several categories of work, such as fitting, welding, rigging, plumbing, pneumatics, hydraulics, electrics and/or operating equipment. A single status workforce is one where all workers are on salary covered by a negotiated contract with similar working conditions such as hours of work, leave, superannuation, uniform, etc., with the only difference being the salary package.

These two aspects has resulted in a substantial reduction in the number of people required to operate and maintain a plant to a defined target, to the point that a crew is not directly supervised. Work attitudes have improved and productivity increased. The resentment between workers and management has been reduced as the demarcation between "them" and "us" has become blurred. However, there is, and always will be, room for improvement, if for no other reason than to stay competitive.

Sophisticated as it is, a SCADA system does have some limitations. Basically, it shows a process on monitor screens as it is and records the history of the process in a database. For instance, it shows on monitor screens, by the use of touch sensitive keyboards, what equipment is running, in what direction and at what speed, the level of material in a storage bin, the pressure and/or temperature of a reaction, the movement of a valve, the weight of ingredients, or items used in the process. Historical data can be retrieved from the database going back two hours, two days, two months, or two years, if such data has not been purged from the system in the mean time.

Thus, a SCADA system provides the data on which an operator makes a judgement as to the way the process is progressing. The SCADA system does not explicitly advise the operator that the process is about to go out of control, and why it is going out of control, though that information is available for interpretation in the database. The operator thus tends to be reactive rather than proactive to changes in certain process variables.

An improvement and refinement to the existing system is the provision of a means to oversee and continuously monitor the SCADA system to advise the operator when and why the process is going out of specification. The following sections outline the development of such a facility.

1.2 The Anode Production Process

1.2.1 Overview

In the smelting of aluminium, a high DC current at 4.5V is passed between a cathode and anode across a molten bath in an electrolytic cell, or pot. The electrolyte consists of fluorides of aluminium, sodium and calcium in which alumina has been dissolved. The anode is sacrificial and consumed by the electrolytic process. Aluminium is drawn off each day and the anodes replaced to a pre-determined schedule.

An anode is a conglomerate of variously sized coke particles, coke fines and liquid pitch that has been mixed in a heated mixer and then formed into a "green" anode by compression or vibration in a mould box. The Green Carbon Plant, comprising storage bins, screens, coke dryers, crushers, conveying equipment, mixers, presses, dust collectors, weigh scales, heat transfer oil heaters, liquid pitch heating and handling facilities is operated through a SCADA system using data provided by programmed logic controllers.

The green anodes are conveyed to a furnace wherein they are cured in a computer controlled heating-baking-cooling cycle taking about two weeks. Thence, the "baked" anodes are conveyed to the Rodding Room and married to a copper or aluminium rod to form the completed anode assembly. These anode assemblies are transported to the potlines for "setting" in the pots. In order to cater for scheduled and unscheduled plant shut downs, there is storage for green and baked anodes and for the completed anodes assemblies.

Since the anode is consumed by the electrolytic process, it requires replacement against a fixed rota based on the expected anode life, even though some anodes of higher quality could be retained longer than this mean. The longer an anode can be left in a cell before being replaced, the lower the operational cost relating to its use. Thus, if all anodes were produced with physical and chemical properties of a consistent high quality, the expected mean life, and therefore the changing rota, could be increased. This would lead to a reduction in the operational cost of producing anodes.

An example of an aluminium smelter is that of Comalco at Bell Bay in Tasmania, where there are 544 pots each with 20 anodes. The 350kg "green" anode is formed from carbon paste that has been mixed at a temperature of 160°C for 50 minutes in a 4t rotary mixer and then compressed in a 2000t press. An anode is replaced every 14 days, resulting in 280,000 anodes having to be made each year. A new baked anode weighs 330kg while a used anode butt weighs about 80kg, said butt being re-cycled. Thus, 70,000t of raw materials plus power and fuel oil are required each year to make these anodes. Extending the rota by one shift, 12 hours, by improving the consistency and thence quality of the anodes would result in substantial cost savings.

1.2.2 The Manufacture of Green Anodes

The forming of anode blocks is carried out in the Green Carbon Plant. Figure 1.1 shows a schematic of the anode production process. Coke is conveyed from a stockpile in the open to storage bins, thence it is dried, if necessary, in a kiln, screened and/or crushed into various sized fractions for storage in bins. Butts and green scrap are also screened and stored in their respective bins. Some of the coke is passed through a ball mill to generate fines - particles of size less than 300μm - at the rate of 8t/hr. Dust generated by these conveying, crushing and screening operations is collected via a vacuum system in dust collectors for use as superfines in the anode forming process.

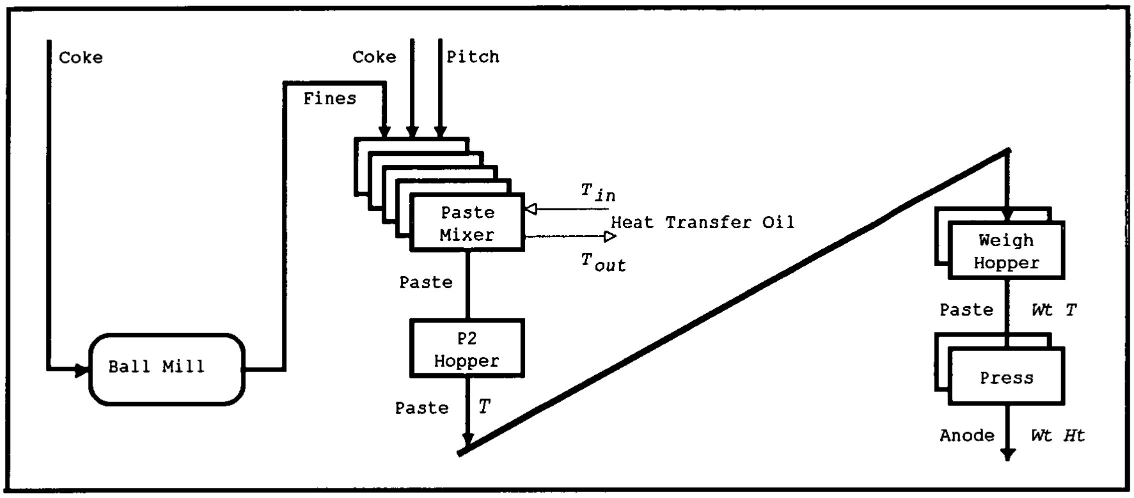


Figure 1.1: Schematic Diagram of the Anode Production Process

The final ingredient is liquid pitch which is used to bind the various sized fractions, butts, green scrap, fines and superfines to form the resulting carbon anode. Pitch is stored in liquid form at 180°C remote from Green Carbon and pumped through electrically heated pipework thereto.

The various dry ingredients, grist, are fed into a batch weigher according to a pre-set recipe and then conveyed into one of five heated mixers where a measured amount of liquid pitch is added. The ensuing paste is mixed and heated for about 50 minutes to 160°C by heat transfer oil (HTO) pumped from the HTO plant through the mixer heating jacket and returning to the HTO plant. The HTO and pitch plants are oil fired utilising heavy fuel oil to heat the heat transfer oil to 260°C.

A mixer is emptied in turn every 12 minutes onto a belt which feeds the paste into a holding bin. Should there be a delay in emptying a mixer, the paste temperature is controlled by shutting valves on the HTO pipework to the respective mixer. The paste is thence conveyed to the top of the anode presses via an inclined belt. Since there is a temperature limitation of 200°C on these belts, paste of a higher temperature than 200°C is scrapped by dumping at either of two places. Up to 1% of production is scrapped in this way. Once the paste leaves the mixer, there is limited control over its rate of cooling by way of spraying the paste with a water spray just prior to batch weighing. The batch weigher discharges a mix into the press mould where it is formed into an anode at the rate of one every minute. On being ejected by the press it is weighed and its height recorded. Should the height lie outside set point limits, it is automatically sent to scrap for re-cycling. Green anodes may also be rejected manually for various process reasons, such as being too weak or falling apart on the conveyor. Green scrap accounts for up to 1% of production. Sound green anodes are conveyed to storage or to the baking plant.

1.3 Process Control

A Honeywell control system addresses all aspects of Supervisory Control and Data Acquisition (SCADA). The system architecture uses a central mini-computer that serves multiple remote operator stations based on PC's linked to the plant network to maintain both real time and historical databases. The VAX system is fully networked. Each operator station runs a package called IPS (integrated personal station) to maintain graphic displays and access the data manager. This allows general purpose personal computers to be used by supervision, technical and maintenance personnel to access process information directly without dedicated equipment.

Front line control of the Green Carbon Plant utilises programmed logic control (PLC). For the purposes of control and data acquisition, the SCADA system polls about 1800 point values at either 5 second or 60 second intervals through a data highway link with the PLC's. A point value is either a status of an item of equipment, ie on, off, forward, reverse, overload, under-speed, open, closed, high fire, low fire etc., or a value, ie percentage full, motor current, belt speed, paste temperature, anode height, anode weight, fines weight, percentage open, etc. The SCADA system sends data to the database as required and designed into the system. For instance, though the point value of the paste entering the weigh hopper is being polled every five seconds to show the hopper filling on the monitor screen, the actual paste weight sent to the database is the maximum value. Those point values that are likely to be of value for later analysis are stored in the database, whose archiving capacity is only limited by the hardware installed. For instance, in Table *GC_anode,* data relating to a single anode is stored in a single line, or tuple, in the database, ie date and time stamp, press no., anode type, year, month, day, hour, minute, shift, weight, height, ASG, paste temperature, maximum press pressure, end-of-shift summary, month total and paste weight.

The display on the operator station monitors are updated every 15 seconds. Through a station, the operator can directly control the process by stopping or starting equipment, open or shut valves, change set points, change the paste mix recipe, change motor drive speeds, change motor direction, etc. Due to the limited size (20") of a monitor screen and the complexity of the process, it is not possible to display the whole process in detail on a single screen. Instead three screens are used with facilities on each to zoom in (and out) for more detailed information. Relevant screen displays are shown in Appendix 1. The system also has full statistical functionality allowing charts to be customised to display historical trends of process parameters in real time.

1.4 Critical Aspects of the Process

Process variables affecting anode properties are:

- Sizing of fines material
- Percentage of pitch
- Mixer paste temperature
- Press paste temperature
- Press pressure

Research has indicated that variation in the fines preparation, paste mixing and anode forming processes critically affect the ultimate properties of the anode [Meier, 1996] [Sowerbutts, 1993]. Thus, it is important to minimise the variation in process variables at this early stage in the manufacture of an anode. The accent is on controlling and reducing variation, as a high variation implies a lack of control. Thus, when the degree of variation of process variables can be controlled, then the properties of the anode can also be more readily controlled. In order to do this, it is necessary to present data to the operator in such a way that he can take steps to maintain process variables within set point limits.

One of the most important operations in anode production is in the fines preparation. Every particle in the conglomerate is coated with pitch in the mixing process. The combination of pitch and fines provides the binder material in the conglomerate to fill all the voids between the larger particles. The percentage of pitch in the paste is such as to provide the finished product, the anode, with the optimum of properties. Volume for volume, the finer the particles the more pitch required to coat each particle to a given thickness. If the percentage pitch stays constant and the sizing of fines is coarser than optimum, then the paste covering on each fines particle becomes thicker than optimum and the paste is said to be over-pitched. Conversely, if the sizing of fines is finer than optimum then the coating of pitch on each fines particle becomes thinner than optimum and the paste is said to be under-pitched.

With a coarse fines and the resultant over-pitching, there is an excess of pitch coating a particle. Thus, when the volatiles are driven off in the baking process, voids and porosity increases. There is also an excess of voids due to the relative coarseness of the material and a failure to properly pack all the voids with fine material. Furthermore, in the baking process not all of the volatiles are properly driven off and some of the volatiles condense on the surface between adjacent blocks in the cooling phase causing the blocks to stick together. The end result of fines being too coarse is excess porosity, a weaker block, a block with a tendency to crack leading to a shorter life in the pot, and a greater voltage drop across the anode when in a pot leading to a higher power consumption.

With a fine fines and the resultant under-pitching, there is a loss of strength due to the relative paucity of pitch to bind the particles together. Also, since the fines are not adequately bound to each other, they separate from the anode when in the pot to form a dust. This dusting effect upsets the pot chemistry, causing problems. To avoid these problems, the current practice in manufacturing anodes is to slightly over-pitch.

The temperature of the paste in the mixer is very important. It is essential to obtain a sufficiently high temperature to properly coat all the coke particles with a film of pitch and obtain a homogenous conglomerate. Ideally, the temperature of the paste discharged from the mixer should be within 5°C of 160°C to ensure that it has been properly mixed. Since the paste is transported some distance from the mixers to the presses there is scope for it to lose temperature naturally. Further cooling is obtained by spraying the paste with a water spray. Ideally, the temperature of the paste entering a press should be within 2°C of 120°C to ensure adequate strength during the many handling operations. If the temperature is too low the resulting anode will be friable and break up, while if too high, the anode will slump, lose shape and also break up.

The pressure exerted on the paste in the mould in the block forming process is important, though some work is still going on to determine the optimum pressure. Up until ten years ago it was thought that the higher the pressure the better. The high incidence of horizontal surface cracks gave rise to a re-think of this practice and the ram pressure has since been incrementally reduced from 30MPa to 14MPa with some reduction in surface cracking.

The foregoing parameters affect the strength and performance of an anode in a pot. A dimensional restraint is the height of the anode. Too high and it will not fit in the baking oven or a pot. Too low and it will not last the distance in a pot and have to be replaced early. However, height sensors cause an anode to be automatically rejected to scrap if its height is not within 10mm of set point. The height sensor is manually checked every shift.

A measure of the density of an anode is its Green Apparent Density (GAD), a function of its height and weight, which is an important quality figure to characterise the anode's performance in a pot. It is a measure of how closely packed the anode aggregate is. The higher the density, the slower an anode is consumed in the electrolytic process in a pot. A higher density also implies a more consistent macroscopic structure resulting in a lower electrical resistivity. While the aim is to achieve a high GAD, if an anode's density is too high, it tends to be brittle and prone to cracking from thermal shock.

1.5 Process Monitor Specification

The operator monitors the process utilising information provided by the SCADA system on Video Display Units, which show *what-is* rather than *what-will-be* or *what-caused* the prevailing process conditions. Information relating to potential problems or causes of existing problems is available, which a very experienced operator can obtain by querying the SCADA system. In practice, the operator tends to rely on the control system itself to control the process within its own limitations, since more pressing problems usually divert him from this fine tuning task. The operator sees data relating to each anode or mixer batch as it is occurring, which varies from the previous set of data, and may fail to notice a trend away from a set point. In general, there is too much data to assimilate for the operator to properly control the process. Thus, anodes are produced that generally meet specification, but with some degree of variability.

In an effort to provide the operator with a means of reducing these variabilities and tighten process limits, it was proposed to develop a facility to monitor the SCADA system in the areas of concern. The specification outline for this facility is:

- Facility location: Operation room with access over the network to other users.
- Users: Operators, experienced and in training, the supervisor, superintendent, development engineer and manager.
- Monitoring mode: Continuous over a 10 day production run, cycling every 10 minutes or so.
- Processes covered: Fines production
Paste mixing
Anode forming
- To display: Statistical process control charts for specific variables.
Warning when a variable goes outside set point limits.
Cause for variable going outside set point limits.
Standard Operating Procedure for a given problem.
Other pertinent data as required.

To meet this specification, the facility has to:

- access the SCADA database for current data,
- access the SCADA system for point values,
- statistically analyse the retrieved data,
- generate and display statistical process control charts,
- determine any potential process problems and their cause by the application of heuristic based rules and logic,
- display messages re status of each stage of the process with relevant SOP's if necessary.

The basis for the analysis is the examination of historical data for each specific variable for the two hours (say) prior to the time of monitoring the system. Said data can be imported from the database for trending and charting into Microsoft Excel, into a proprietary statistical process control software package or into a specially written program. The disadvantage of using Excel is that the generated chart does not adequately display process trends. To do that, one has to use a dedicated software package. That in itself would provide useful information to an experienced operator, but would be of limited use to other users. Even an experienced operator would have to search the SCADA system for additional information in order to arrive at the cause of a problem. Thus, this option does not meet the requirements of the specification, though the dedicated software package could be called on for use by another application.

Having analysed and trended the requisite data, it is then necessary to determine any potential problem and its cause by formulating and applying a set of rules based on logic and heuristic knowledge. This can be done by straight-out programming in, for instance, Lisp, C or C++, or by the use of a single proprietary software package, if available. In the application of these rules, point values from SCADA have to be obtained, which can be done by utilising the Direct Data Exchange (DDE) capabilities of Microsoft Excel or by writing an Application Program Interface (API).

Basically, then, to meet the required specification, there are two options:

- Customised programming of the rule base and of the links with SCADA and proprietary software packages such as Microsoft Access and Excel and a statistics package.

- Find a single proprietary software package to perform all the required functions, ie with the core of the system providing a means of editing and applying sets of rules together with peripheral tools such as interface facilities for holding conversations with databases and control systems, kits for using external programs and language calls, graphics and debugging aids.

The former option demands wide computer programming skills besides an in-depth knowledge of the process under consideration. On the other hand, and if available, the latter option would encompass a software shell providing a collection of tools for use by programmers and/or other professionals who might not have a wide range of programming skills.

In both options, programming of the rule base and the control module is required. Knowledge of the means of communicating with SCADA, Access, Excel and writing API's over a network is also required. However, additional programming time and expertise is required for the former option to integrate the dedicated programs that provide the features such as statistical analysis, charting, accessing the database, accessing the control system, the relay and storage of messages. This programming also necessitates additional testing and debugging.

Therefore, without diminishing the problems involved, the latter option appears the most favourable if there is a proprietary software shell available that incorporates the required features.

There have been reported [Okuda and Miyasaka, 1990] [Pham, 1988] [Villa, 1992] uses of techniques developed around the application of Artificial Intelligence, specifically utilising expert systems, for monitoring processes. Before discussing their application to this project, a brief overview of Artificial Intelligence is presented together with the considerations that led to the choice of an appropriate software package.

2. ARTIFICIAL INTELLIGENCE AND THE PATH TO A SOLUTION

2.1 Definition

What is *Artificial Intelligence* (AI)? It sounds like a substitute for the real thing. *Artificial* means *made in imitation of* or *made by man* while *intelligence* means *having the ability to reason.* So, maybe a definition of AI is "A machine provided with the ability to reason (by man) has Artificial Intelligence."

The most quoted definition of AI is that due to Turing (1950). His proposal for whether, *AI or NOT AI*, is called the Turing Test, ie "If, in a totally unlimited conversational setting without peeking or verbal communication, people are unable to distinguish between a person and a machine, then that machine embodies AI".

An anonymous, but widely used definition is that "AI is the study of computers doing tasks that would be considered to require intelligence if a human did them".

Another definition attributed to Rich (1983) is that "AI is the study of how to make computers do things at which, at the moment, people are better".

Memmi (1989) has argued that the word intelligence is too narrow and instead the term cognition should be used to include visual perception and language as well as problem solving.

Some definitions relate to a branch of AI but by definition exclude other branches that are excepted as recognised sub-domains of AI. To illustrate, Haykin postulates that an AI system has three key components, representation, reasoning and learning. This rules out expert systems as a branch of AI, since expert systems generally only encompass the first two components.

There are many definitions of AI. While some appear to be fairly comprehensive, flaws in the argument for said definition can usually be found that detract from its completeness. This is not the place for a debate on the issue, but merely to indicate that there does not appear to be one, single definition that encompasses the study and use of all applications of AI.

Over the past twenty years or so, AI has emerged from the laboratory and progress from being a collection of disparate computational approaches to problems in other subjects. This disparity between sub-domains of AI is a reflection of AI's immaturity as a science, though some purist computer scientists would dispute that AI is a science at all, or that it is even a branch of computer science. [Partridge, ch.2] It could be argued that the only link between AI and computer science is the use of the computer purely as a tool. Be that as it may, while work in some branches of AI, eg neural networks and genetic algorithms, is still basically in the realm of research, work in other branches, eg fuzzy logic and expert systems, is being carried out in commercial, financial and industrial applications, albeit in a small way.

The domain of Artificial Intelligence covers a score or so of AI models, several computing languages and a multitude of techniques. In order to provide a background to the subject, some of the major aspects are briefly described below, with more emphasis being placed on aspects that might directly relate to this project.

2.2 Machine learning

Machine learning has many applications such as, medical diagnosis, classification, protein design, problem solving, natural language acquisition and processing, vision, robotics and developing expert systems.

Machine learning is the automated acquisition of knowledge, which, by such acquisition, leads to an improvement of performance [Schlimmer]. Developing machine learning has been the catalyst in understanding the learning process in general and has led to several learning models, namely, Darwinian selective learning, supervised learning, unsupervised learning, reinforcement learning and several more [Haykin ch.2].

While machine learning is considered to be a sub-domain of AI, there are two key senses in which machine learning is also an integral part of the larger field of AI [Schlimmer]. First, one must consider central AI issues of knowledge representation, memory organisation and performance. Secondly, learning can occur in any domain requiring intelligence whether the basic task involves classification, problem solving, reasoning, natural language processing or vision. Thus, one can view machine learning more as a framework for AI research and development than as a sub-domain.

There are several aspects whereby learning models differ, namely:

- the representation of experience
- the representation of acquired knowledge
- the performance task
- the difference between supervised and unsupervised learning
- the difference between incremental and non-incremental learning
- the notions of induction and explanation

Each of these aspects attract different algorithms and methods in their application which are broadly categorised as:

- neural network learning methods
- empirical methods for inducing rules and decision trees
- genetic algorithms and classifier systems
- analytic learning methods
- case based approaches to learning

Each of these paradigms are discussed in more detail below.

2.2.1 Neural Networks

Historically, artificial intelligence grew out of work in neural networks in the 1940's and 1950's [Haykin, ch.1]. In 1961, Minski wrote a paper entitled "Steps towards Artificial Intelligence" which contained a large section on neural networks. Neurons are structural constituents of the brain. It is estimated that there are ten billion neurons connected to each other by 60 trillion synapses creating a highly complex, non-linear and parallel computer or information processing system. One might think at times that the brain is rather slow at reasoning over a problem and certainly, with a few exceptions, is unable to match the speed of a computer doing repetitive calculations. However, when it comes to comprehending or recognising a face, a scene, handwriting, or a voice over the telephone, it surpasses the best computer, ie a parallel processing Cray, by many orders of magnitude.

In trying to emulate the function of the neuron in the brain by developing artificial neural networks, it was hoped to increase the power of the computer as well as gain a better understanding of how the brain functioned. To this end, several disciplines are involved working together and separately, notably, mathematicians, computer scientists, neurologists, neuro-psychologists and specialists in (artificial) neural network theory.

Early work in the 1960's involved single, two and three layers of neurons with a number of inputs to produce a single output. For various reasons, little progress was made until the 1980's, when, with the advent of the personal computer and new theories of self-organisation, feedback within networks and storage of information in dynamically stable networks, interest and progress in neural modelling took off.

A network is "trained" by presenting it with a large number of sample inputs together with known correct outputs. Gradually the strengths or weights of the internal structure are altered in accordance with an in-built strategy until it produces a correct response each time. The network should then operate correctly on new inputs that are different to those in the training set.

The majority of effort in the application of neural networks has gone into pattern recognition, eg speech, handwriting and vision, and intelligent control in conjunction with fuzzy logic techniques.

2.2.2 Induction Methods

While development work is being carried out in all five of the main areas of machine learning referred to, induction techniques as applied to empirical learning methods are attracting the most attention. A problem with developing expert systems (refer section 2.3) is that the process of acquiring the knowledge from the expert is tedious, expensive and not necessarily accurate or appropriate. Feigenbaum (1981) is quoted as saying: *There are many important problems of knowledge representation, utilisation and acquisition that must be solved, but the acquisition problem is the most critical "bottleneck" problem.* Quinlan (1987) has shown that machine learning techniques can provide the knowledge in a more efficient manner. In an effort to bypass this bottleneck, the role of the expert is changed to that of providing a base structure of the discipline, the knowledge itself being induced from examples and observed data. The expert then carries out the fine tuning as required.

The essence of induction is to move from a set of known examples to a theory that explains both those examples and other examples as well. Thus the rule cannot be expressed solely as a tabulation of the known set since nothing can be said about the class of an unseen object, but must generalise from it (the original set). The rule is expressed in the form of a decision tree. An example of this approach is Quinlan's use of an induction reference tool, C4. One experiment involved the determination of the rule for a thyroid condition from 19 information attributes and 15 diagnostic conditions from over 3000 cases, of which 800 were unseen. The resulting decision tree accurately classified 99% of the unseen cases. The experiment demonstrated that high performance rules can be generated from data with the sort of blemishes commonly met in the real world, ie missing information and mis-information.

2.2.3 Genetic Algorithms

Genetic algorithms are a family of search methods that derive their name from an analogy with genetic change in a population of individuals. Holland (1962) is attributed with laying the foundations of the application of nature's genetic search algorithms to AI. His goal was to develop the theories and procedures necessary for the creation of programs and machines with the capability to adapt to arbitrary and changing environments.

The object of the search is to find the best in a population of experiences or structures. Conventional optimising and search methods use hill climbing and/or random walk search techniques [Goldberg, ch.1]. Except in small populations, both methods are very inefficient in that they use a comparatively large effort to find the ultimate best or miss it altogether. Genetic algorithms are search methods based on perceived natural selection methods, are more efficient in the use of resources and rarely (by definition, in nature, never) miss. Genetic algorithms follow three steps in processing new experiences: updating pattern strengths, applying search operators and pruning ineffective patterns.

In genetic algorithms, instances and events are assumed to be represented by sets of knowledge structures that are not joined to each other. Each structure has weights that summarises their performance based on past experience. In the first step, and given a new instance, the contents and weights of individual structures are modified in a way dependent on the algorithm used to arrive at a decision. Each time a structure is successfully matched to an instance it is rewarded by increasing its weight incrementally. Conversely, an unsuccessful match results in a penalty by way of a reduction in the weight of the class. New rules are generated from previous strong rules, credit assigned to useful rules and blame to faulty rules.

In the second step, three search operators are used: reproduction, crossover and mutation operators. Reproduction involves copying a population of functions according to their fitness. Crossover involves the mating of functions at random.

Mutation operators provide a random change to a function. While the reproduction and crossover operators combined provide the power of genetic algorithms, mutation operators provide a means of occasionally capturing an improvement that had been missed by the reproduction and crossover operators.

In the third step, strengths are reinforced while weaknesses are rejected to the point that weak rules and relationships disappear, as there is little point in tying up resources in retaining rules and relationships of little relative value. Thus, the use of genetic algorithms seeks to emulate nature wherein the fittest survive.

The application of genetic algorithms are many and varied, from design in engineering, genes, molecules and drugs to military uses, and to designing investment strategies.

2.2.4 Analytic Learning Methods

In analytic learning methods, existing domain knowledge is transformed into a more useful form using data only to guide the application of deductive processes to this knowledge. The known knowledge is reduced to a set of shorter, intermediate rules to form a proof tree or explanation of how to reach a given goal. Applying analytic learning methods to a given problem and solution pair, helps to focus attention on relevant features of the problem and provide a summary of the general rule. Thus, from this specific case, general rules are constructed to simplify the future search for similar goals. Simplifying knowledge in this manner results in increased efficiency in problem solving tasks.

2.2.5 Case Based Approaches

Humans in general learn from what worked in previous similar situations. Experts in many fields also learn from what worked, or didn't work, in previous instances. Thus it is natural to adopt this approach in constructing AI systems by using knowledge of previous specific cases to classify new cases or to solve problems. However, this abstraction of previous knowledge is not carried out until required. In a given knowledge domain, a knowledge base is compiled. When a new situation occurs, the knowledge base is searched for a best match from the stored instances and the data in that best match used to provide the missing information. The outcome, if positive, is then added to the knowledge base. A good case in point is the medical knowledge domain wherein symptoms of a given disease or medical problem are added to the knowledge base as they are matched to that disease or medical problem.

2.3 Fuzzy Logic

For the past two thousand years or so, western thinking in science, religion and philosophy has been based on the Aristotle binary view of logic, *A AND not-A*, black or white, true or not-true, good or bad, yes or no, 0 or 1 [Kosko 1994]. The introduction of chance and probability still boils down to an event being either this or that. A flipped coin is either heads or tails. An electron is either in one shell or another (let us not confuse the issue with the concept of quantum mechanics). Many paradoxes are paradoxes because they demand an A or not-A answer.

What about greyness? Neither *A NOR not-A*. When is a pile of sand not a pile of sand? This introduces a notion of vagueness or fuzziness. The statement that a person is tall is fuzzy even if tall is defined as someone of height greater than 1.8m. The set of tall people is a fuzzy set. The rule "If a person's height is greater than 1.8m, that person is tall" is a fuzzy rule. Reasoning with fuzzy sets and/or fuzzy rules is known as fuzzy logic.

Aristotelian logic equates to:

Given the rule:	If A then B
and the fact:	A
we can deduce the fact	B

Whereas, the fuzzy logic equivalent equates to:

Given the fuzzy logic rule:	If A then B
and the fact:	A known to be true to some degree
we can say the fact	B is known to be true to a no greater degree than A

A fuzzy rule then, has premises and conclusions which contain imprecise linguistic variables whose values can be represented by fuzzy sets.

There are two main areas of application of fuzzy logic. In both areas, the Japanese lead the world and hold most of the patents. The first area concerns the replacement of the skilled human operator. Notable examples are auto-focussing and anti-image jitter systems in cameras and camcorders, washing machines, vacuum cleaners, air conditioners, anti-lock brakes, fuel injection, automatic transmissions, vacuum cleaners, control in the Sendai subway system and many more. The second area concerns the replacement of the human expert. Notable examples are medical diagnosis systems, traffic control systems, securities fund and portfolio selection systems, expert systems with deductive capabilities, natural language processing and decision analysis in general. Work is currently proceeding in combining fuzzy logic theory with neural network theory to generate adaptive fuzzy logic systems, ie systems that learn [Kosko]. This is another indication of the breakdown of the boundaries between sub-domains of AI.

2.4 Expert Systems

Knowledge-based expert systems, sometimes called knowledge systems but commonly called expert systems, employ human knowledge to solve problems that normally require human intelligence with the elicited knowledge applied electronically [Hayes-Roth, 1992].

The birth of expert system methodology started twenty or so years ago when AI researchers realised that to make a machine problem solver perform as effectively as a human expert, it was necessary to provide the machine with the specialised knowledge of the human expert. This gave rise to knowledge engineering, whereby knowledge is elicited from the expert and represented in a knowledge base. Examples of early applications are INTERNIST [Pople 1975], MYCIN [Shortliffe, 1976] and DENDRAL [Lindsay 1980].

INTERNIST contained 100,000 judgements about relationships among diseases and symptoms in internal medicine and approached a breadth of knowledge and performance beyond that of specialists in the field. MYCIN incorporated 400 heuristic rules to diagnose and treat infectious blood diseases plus explanations for any conclusions generated. DENDRAL identified the chemical molecular structure of a material from its mass spectrographic and nuclear magnetic resonance data.

Conventional programming involves algorithms and data where the algorithms determine how to solve the particular problem and the data characterise the parameters of the problem. Applying human knowledge requires different ways of organising pieces of knowledge into decision making routines. This is not easy, as our understanding of the inherent sophisticated algorithms used by human experts, expressed as know-how, is incomplete. Knowledge systems collect these pieces of know-how into a knowledge base and then access that knowledge base to reason about a particular problem. As a result, knowledge systems differ from conventional programs in the way they are organised, in the way they deal with that knowledge, the way they execute the program and the way they interact with the user. Knowledge-based systems simulate human expert knowledge and performance, hence the term, *Expert Systems.*

An expert system then, is a computer program that uses knowledge, facts and reasoning techniques to solve problems. Its architecture has two main components: the knowledge base and a separate inference engine. The knowledge base contains the facts and rules, while the inference engine contains the strategies for controlling the selection and application of the knowledge and rules of the knowledge base.

2.4.1 Knowledge Acquisition

Knowledge not only encompasses knowledge available from books and the written word, it also encompasses heuristics, ie rules-of-thumb, observations, judgements and other forms of fragmentary knowledge which is represented by logic, rules, classes and structures. So an important part of developing an expert system is the acquisition of the knowledge, seen by many as the hardest part. There are three categories of eliciting knowledge: manual, semi-automatic and automatic.

In the manual method for eliciting knowledge, the knowledge engineer interviews and observes the expert(s) over a period of days, weeks or months. This also involves determining why the expert arrived at a particular decision, questioning the validity of a decision in the light of the knowledge engineer's understanding of a particular problem and extracting information and knowledge from written or computer based sources. It is extremely time consuming, might not extract all available knowledge and might even extract knowledge that is not accurate. The expert might not be able to verbalise the reasoning behind his judgement, his reasoning might be wrong, or inconsistencies might well reveal themselves in the development of the expert system, hence the need for further questioning.

In the semi-automatic method, the expert builds the knowledge base with a computer aided interactive interviewing facility with some help from the knowledge engineer. In particular cases, this method tends to be more efficient as it allows the knowledge engineer more time to understand the problem and query the expert's judgement and reasoning processes.

In the automatic method, the role of the expert and knowledge engineer is minimised. The knowledge base is built up from case histories and examples, with the rules induced from the knowledge base. These rules are reviewed by the expert and modified if necessary. This method is most suited to large classification type problems, especially where answers to a question are of the yes-no variety and exceptions and uncertainties are not present.

2.4.2 Search and Inference

Problems are solved by searching for a solution, where, in some cases, the number of possible solutions can be very high. An additional variable to be contended with is uncertainty, which can be dealt with by using confidence factors in conjunction with probability theory or fuzzy logic, or by non-numeric methods. There are two basic forms of search mechanism, forward and backward chaining, where:

- Forward chaining involves searching from known facts and rules to new deduced facts.

- Backward chaining works back from a conclusion to find the supporting facts.

The search and pattern matching operation is carried out by the inference engine which examines the rules in sequence looking for matches to the current conditions in the data base. As rules matching these conditions are found, the rules are fired, thus initiating the rules specified. As the rules continue to fire, they will reference one another and form an inference chain. The firing of a rule may add new data to the data base providing additional evidence to work on. The process of working through the rule base continues until a solution is found, with one possible solution being that a solution is not found.

In forward chaining, the inference engine attempts to match a fact to the left hand side of an IF..THEN statement. In backward chaining, the inference engine attempts to match the right hand side of an IF..THEN statement.

As an example, suppose the rule base is:

IF air lock in fuel line THEN car will stop
IF engine seized THEN car will stop
IF electrical fault in ignition system THEN car will stop

IF steam coming from radiator THEN radiator out of water
IF radiator out of water THEN engine will seize
IF car out of petrol THEN car will stop

An initial fact is:
steam coming from radiator

It is necessary to establish that:
car will stop

Using forward chaining:

The inference engine tries to match the initial fact with the left hand side of each rule in turn till there is a match. There is, with:
IF steam coming from radiator THEN radiator out of water

It compares this rule with the hypothesis. It does not fire but instead infers a new fact *radiator out of water.*

It then tries to match the new fact *radiator out of water* with the left hand side of each rule in turn till there is a match. There is, with:
IF radiator out of water THEN engine will seize

It compares this rule with the hypothesis. It does not fire but instead infers a new fact *engine will seize.*

It then tries to match the new fact *engine will seize* with the left hand side of each rule in turn till there is a match. There is with:
IF engine seized THEN car will stop

It compares this rule with the hypothesis. It fires and proves the hypothesis that:
IF steam coming from radiator THEN car will stop.

Using backward chaining:

The inference engine tries to match the hypothesis with the right hand side of each rule in turn till there is a match. None of the rules fire but there is a match with the first rule:

IF air lock in fuel line THEN car will stop
to infer a fact *air lock in fuel line*.

It compares this fact with data in the data base. It is not there. So it then compares the fact *air lock in fuel line* with the right hand side of each of the rules without success.

The inference engine then tries to match the hypothesis *car will stop* with the right hand side of the second rule. There is a match:

IF engine seized THEN car will stop

to infer a fact *engine seized.*

It compares this fact with data in the data base. It is not there. So it then compares the fact *engine seized* with the right hand side of each of the rules. There is a match with the fifth rule, ie:

If radiator out of water THEN engine will seize

to infer a fact *radiator out of water.*

It compares this fact with data in the data base. It is not there. So it then compares the fact *radiator out of water* with the right hand side of each of the rules. There is a match with the fourth rule, ie:

IF steam coming from radiator THEN radiator out of water

to infer a fact *steam coming from radiator.*

It compares this fact with data in the data base. It matches proving the hypothesis that:

IF *steam coming from radiator THEN car will stop*

Some expert systems only support one of the above strategies, while others support both. In either event, there might be the option of stopping the search once a solution is found or carrying on until all solutions are found. In large systems, forward chaining can be very slow while backward chaining can get fixated on a particular possible solution and finish up in a dead end. Some systems allow both strategies to be used concurrently, thus speeding up the search considerably and ensuring a solution if a solution exists. In the final event, the choice of which strategy to adopt is dependent on the problem, the size of the system and the expert system and/or software package used.

2.4.3 Interfacing with the Outside World

An expert system has been likened to an expert. In order for an expert to make a decision, he has to obtain data from various sources, manipulate that data and present his conclusions in some form. Likewise, an expert system may need to access external (to the application and even to the PC) sources to obtain data relevant to a process, say, being monitored. This might entail holding a conversation with a database or control system and might necessitate the use of a program written in Lisp or C++, say, in order to hold that conversation. Additionally, it might be necessary for the application to display the results of the analysis on screen, or to file, or on other PC's on a network, or generate a hard copy report.

2.4.4 Requirement for an Expert System

Of all branches of AI, the application of expert systems has had the greatest impact outside of the laboratory. In many walks of life, there are pressures to use one's time more effectively, to minimise the carrying out of routine matters, to automate processes, to push decision making down to lower skill level, even to the machine level. These pressures, coupled with advances made in AI research, led to a requirement for, and use of, expert systems. Some of these requirements are:

- To capture knowledge that might be lost through the retirement or resignation of an expert.
- To make diagnosis of a problem easier and more reliable.
- To remove the need to consult an expert for the solution of routine problems.
- To make (expert) knowledge more readily available to others.
- To provide a means of automatically controlling a process.

While expert systems have been applied in many diverse fields outside of the laboratory, it is relevant to refer to a few examples of the application of expert systems to process control.

In the early eighties, Blue Circle (UK) used a LINKman expert system to reduce their energy costs by 60 pence per tonne of cement at Hope Works resulting in savings of £600,000pa in 1982 costs. A similar system has been installed in other plants [Pham, 1988].

An expert system utilising multiple aspect process modelling was developed for dynamically monitoring and diagnosis of 62 processes in a co-generation plant in Osaka [Okuda and Miyasaka, 1990].

An expert system incorporating causal and heuristic models and utilising vision technology identified, diagnosed and repaired, if possible, exposed defects of a flowcoating of TV screens on a production line [Villa, 1992].

To sum up, Expert Systems have been developed in response to a need to capture the knowledge of one or more experts, to solve problems and to provide a tool for those lacking the knowledge of the expert(s) or those lacking the time to solve the problem.

2.5 The Means to an End

Having briefly reviewed various aspects of Artificial Intelligence, it is now germane to consider the most appropriate branch of AI, and software package to use, as the basis for this process monitor.

2.5.1 Choosing the AI Model

It has been shown that techniques developed over the past twenty or so years utilised concepts of Artificial Intelligence to solve many diverse problems. It is pertinent at this stage, to summarise the main functions of the various branches of AI in the following table.

Branch of AI	Main Function
Neural networks	Learning and design
Induction methods	Learning and design
Genetic algorithms	Learning, design and self improvement
Analytic learning	Learning
Case based approaches	Learning
Fuzzy logic	Control of equipment and systems
Expert systems	Problem solving

The requirements of the proposed process monitor does not involve learning or control, but, simply, problem solving. The process has to be dynamically sourced for data, the existence of any problems determined, their cause and solution advised to the operator. Clearly, techniques developed in the use of expert systems provide the best framework for developing the proposed process monitor. Furthermore, Payne and McArthur (1990) outlined guidelines for use of an expert system, namely:

- Are one or two people constantly referred to for solving operational problems?

- Does the amount of information going to the end-user tend to be overwhelming?

- Is it necessary to solve control problems?

- Is it necessary to extract data from other systems?

- Is it necessary to present data to the end user?

The first two points relate to whether it is necessary to use any form of assistance at all. After all, if the information is easily determined and widely known, there is no point in providing assistance. However, in this instance, this is not the case as the knowledge as to how to obtain and interpret the required information is known to a only few people. The anode forming process is complex with a large number of potential control problems, and, in order to determine if a problem exists and determine the cause of said problem, it is necessary to access several, albeit related, systems. It is also necessary to present the results of the monitoring to the operator. Thus, the use of an expert system software shell appears to best meet the criteria for its adoption.

2.5.2 Selecting the Software Shell

In order to select an appropriate software package, the requirements of the process monitor are re-stated in the form of a brief specification, namely:

- A facility to edit a rule base with in-built strategies (inference engine) for querying said rule base,
- having debugging facilities,
- having graphic support facilities,
- with ODBC (Microsoft Open Database Connectivity) to access databases,
- with DDE (Microsoft Dynamic Data Exchange) to talk to other Windows programs, specifically Excel,
- with a tool kit for writing API's (Application Program Interfaces) enabling a conversation between the software shell and an external system using a program language such as C, C++ or Lisp,
- with a facility for writing messages to screen and file,
- with the ability to be run on live data in real time, and
- able to be developed on a stand alone PC using Microsoft Windows and NT.

There are several software packages available that provide the above features, namely, KEE, GoldWorks, KBMS, NExpert, XpertRule, Leonardo, ADS, Level5 Object and G3. However, Level5 Object was selected on the basis that:

- it had all of the required features;
- it was relatively inexpensive;
- it had been in use for several years with a large user base in the USA;
- customer support was available in Australia;
- development by the supplier, Information Builders Inc. USA, was on-going;
- the parties involved in the project had some experience in its use.

3. THE EXPERT SYSTEM BASED PROCESS MONITOR

3.1 Knowledge Representations of Expert Systems

Before describing the process monitor for overseeing the manufacture of anodes, it is first necessary to outline the basics of expert system theory.

A representation of an expert system as a block diagram is shown in Figure 3.1. The user accesses the application by keyboard and monitor screen. The application may or may not prompt the user for input depending on the application's function. Thus, if the application is a medical diagnostic aid, it will prompt the doctor for more information until the diagnosis is complete. However, if the application is monitoring a process, the application will prompt the control system that it is monitoring rather than the user. The heart of the system is the knowledge base, in which knowledge can be represented in several ways, by classes or frames, semantic nets, lists and trees and by production rules. Supporting the knowledge base is the data base providing facts, initial and current states. The whole application is controlled by the inference engine, that includes the rule interpreter and control strategy.

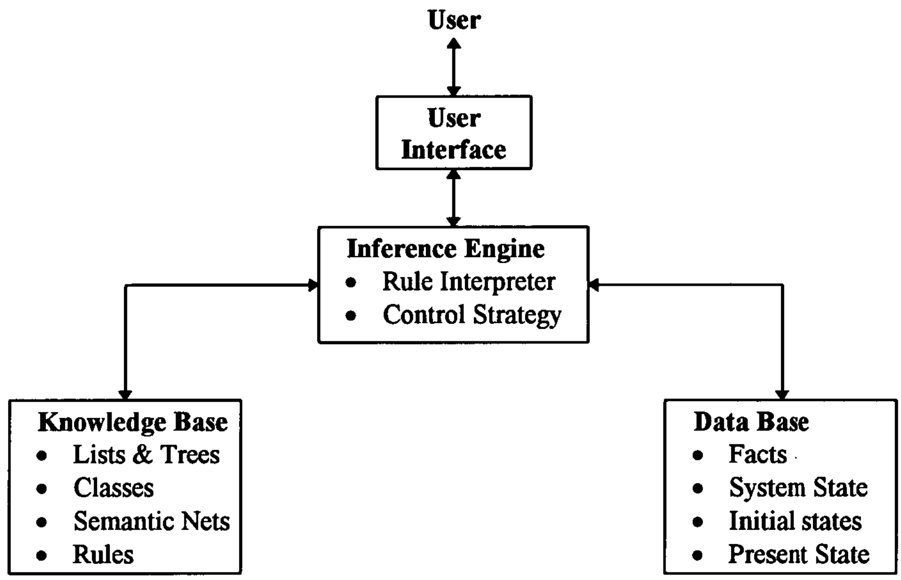


Figure 3.1: Representation of an Expert System

Various features of this expert system model are described in more detail in the following sections.

3.1.1 Lists and Trees

A list is a written series of related items. Lists are used to represent hierarchical knowledge where objects are grouped and graded according to a ranking or relationship. Lists are so widely used in AI that a programming language has been specially developed to deal with them, called LISP, short for LISt Processing.

A tree is a graphical representation of a hierarchy of things or knowledge. Trees are a simple way of illustrating lists not only in AI but also in everyday life, eg the family tree. Another example, illustrated in Figure 3.2, shows the hierarchical structure of transportation.

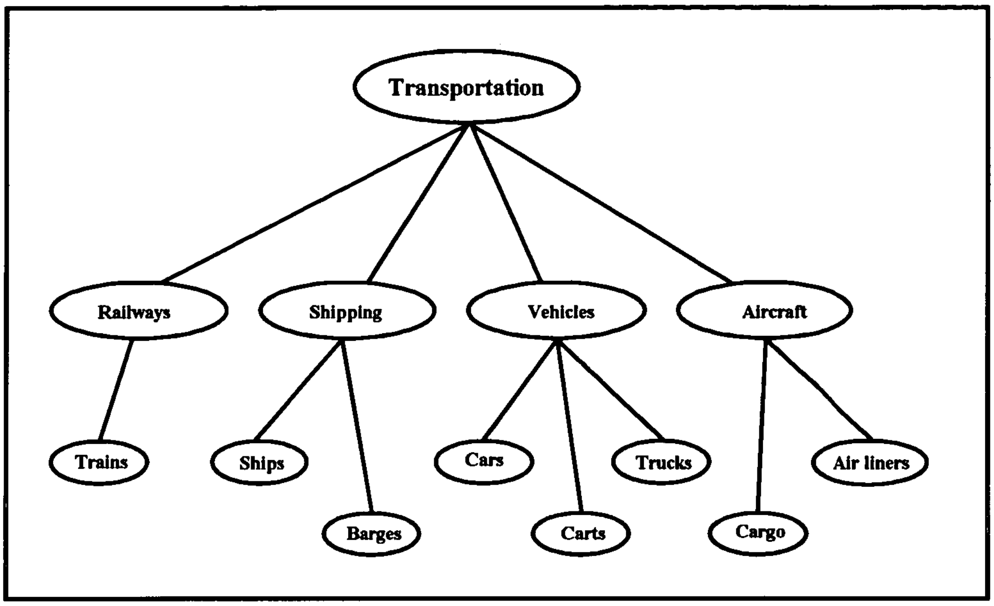


Figure 3.2: Tree Representation of the Transportation Class

3.1.2 Frames or Classes

A frame or class is another way of representing a tree. It is a block of knowledge about a particular object (an object being that upon which attention is directed, either material or abstract) or group of objects, event, situation, location, idea or some other feature. It is a form of collation of facts or statements in one area. A class is further sub-divided into slots or attributes that contain specific characteristics. An example of a class is that of aircraft, as represented in Table 3.1, showing values for a single instance of the aircraft class.

Aircraft Class	Instance
Name of manufacturer	Boeing
Model no.	747-400
Year first manufactured	1988
Seating capacity	421
Wingspan, m	64.4
Overall length, m	70.7
Take-off weight, t	363
Maximum speed, km/h	1050
Range, km	13400
Engine Class	Pratt & Witney

Table 3.1: Frame Representation of the Aircraft Class

In turn, an attribute can reference other classes, eg engine and hydraulics classes. This introduces the concept of inheritance whereby a frame inherits the properties of higher level frames. Thus, an aero engine inherits the properties of the aircraft class, which in turn inherits the properties of the transportation class. Put another way, an aircraft is a form of transport because it inherits the transport property of the transportation class.

3.1.3 Semantic Nets

Another way of representing knowledge is by the use of semantic nets that show hierarchical relationships between objects. By way of illustration, Figure 3.3 depicts a semantic net for the aircraft class.

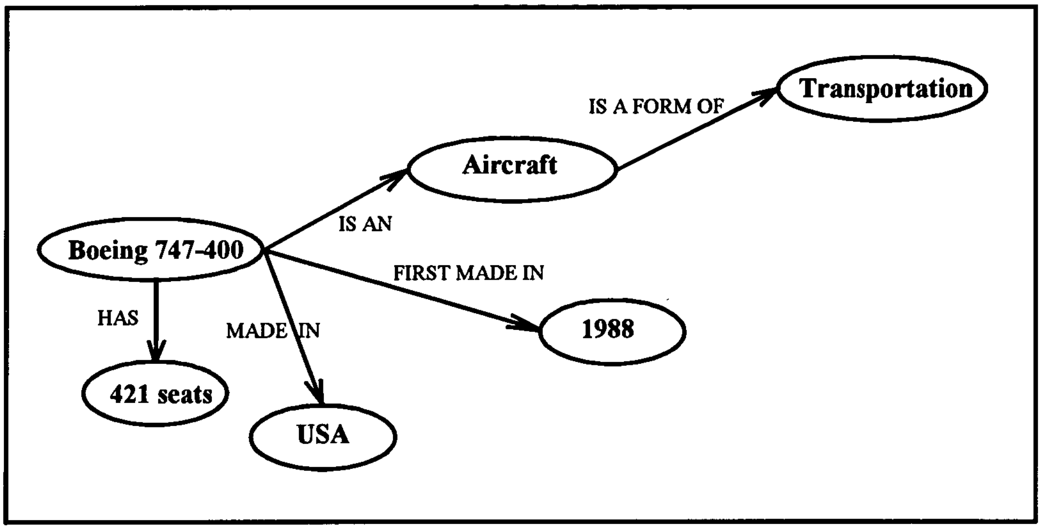


Figure 3.3: Semantic Net Representation of the Aircraft Class

The semantic net is made up of a number of nodes which represent objects linked to each other, where the link describes the relationship between the two (linked) objects. Thus, an *Aircraft* IS A FORM OF *Transportation.* A *Boeing 747-400* IS AN *Aircraft*, HAS *421 Seats* and was FIRST MADE IN *1988* in the *USA*. The IS A and IS AN type link shows that an object belongs to a larger class of objects. Other types of link identify characteristics or attributes of the object.

The semantic network is a flexible way of representing knowledge, with the amount of detail contained depending on the application. Though it is depicted here in a graphical form, in the computer it is represented as a collection of language type statements. When the program is run, various search and pattern matching techniques are used to search through the network structure to determine the answer to a posed question.

3.1.4 Production Rules

Production rules are the most common way of expressing facts. Basically, a rule is expressed in two parts by a statement of the form *IF...THEN*, ie a conclusion follows from a given premise. This format is compatible with the way our minds store and apply knowledge. By way of example:

IF the car runs out of petrol
THEN car will stop.

If the premise is true or the conditions met then the rule is said to have fired. (Note the similarity in terminology with neural network theory wherein a neuron is said to fire when a certain threshold of activity across the synapses of a neuron is exceeded.)

The premise can take the form *IF A*, or *IF A AND B*, or *IF A OR B* or some other combination. The *IF...THEN* statement could also take the form *IF...THEN...ELSE* or even *IF...THEN...ELSE (IF...THEN...ELSE (etc.))*.

Thus:

IF it is fine today
THEN I will walk to work
ELSE I will go by car

Which can become more complex:

IF it is fine today
THEN I will walk to work
ELSE (If my wife does not need the car
THEN I will take our car
ELSE I will see if Bill can take me)

Each rule becomes a node in a tree in the knowledge base which the inference engine searches for a match to a query. Added flexibility arising from the use of production rules is the ease with which existing rules in the knowledge base can be modified and new rules added.

3.2 Knowledge Base

3.2.1 Overview

An anode is a conglomerate of pitch and variously sized petroleum coke particles, mixed together for 50 minutes till the resulting paste has attained a temperature of about 160°C. The paste is transferred to a press to be formed in a mould into a solid rectangular shaped anode 475mm high and weighing about 350kg. The constituents of the anode are liquid pitch, coarse, intermediate sized and fine coke particles, superfines, butts and green scrap particles. Figure 3.4 depicts a schematic of the green anode class which shows the proportions and sizing of the various constituents of a typical recipe.

Green scrap is scrap material resulting from this anode forming process. Butts are the remains of an anode after it has been removed from the potline cell. Butts and green scrap are crushed and screened to a given particle size. Coarse and intermediate sized particles are generated by crushing and screening raw coke. The undersized material from this screening process is passed through a ball mill to generate fines. Airborne dust generated by all of these crushing, screening and milling operations are collected by a dust extraction system and re-cycled as super fines. The liquid pitch provides the binder between the solid particles. As described in section 1.4, too much pitch results in anodes having sub-optimal properties with a tendency to stick together in the baking plant. Anodes with not enough pitch results in anodes being too weak to withstand handling and also leads to dusting problems in the pot. The percentage pitch is based on the total weight of the constituents less the weight of green scrap. The proportions and sizing of the constituents are such that an anode is produced with the required mechanical and physical properties to meet the expected process duty with less than 2% being rejected on account of over- or under-size, or lack of mechanical strength.

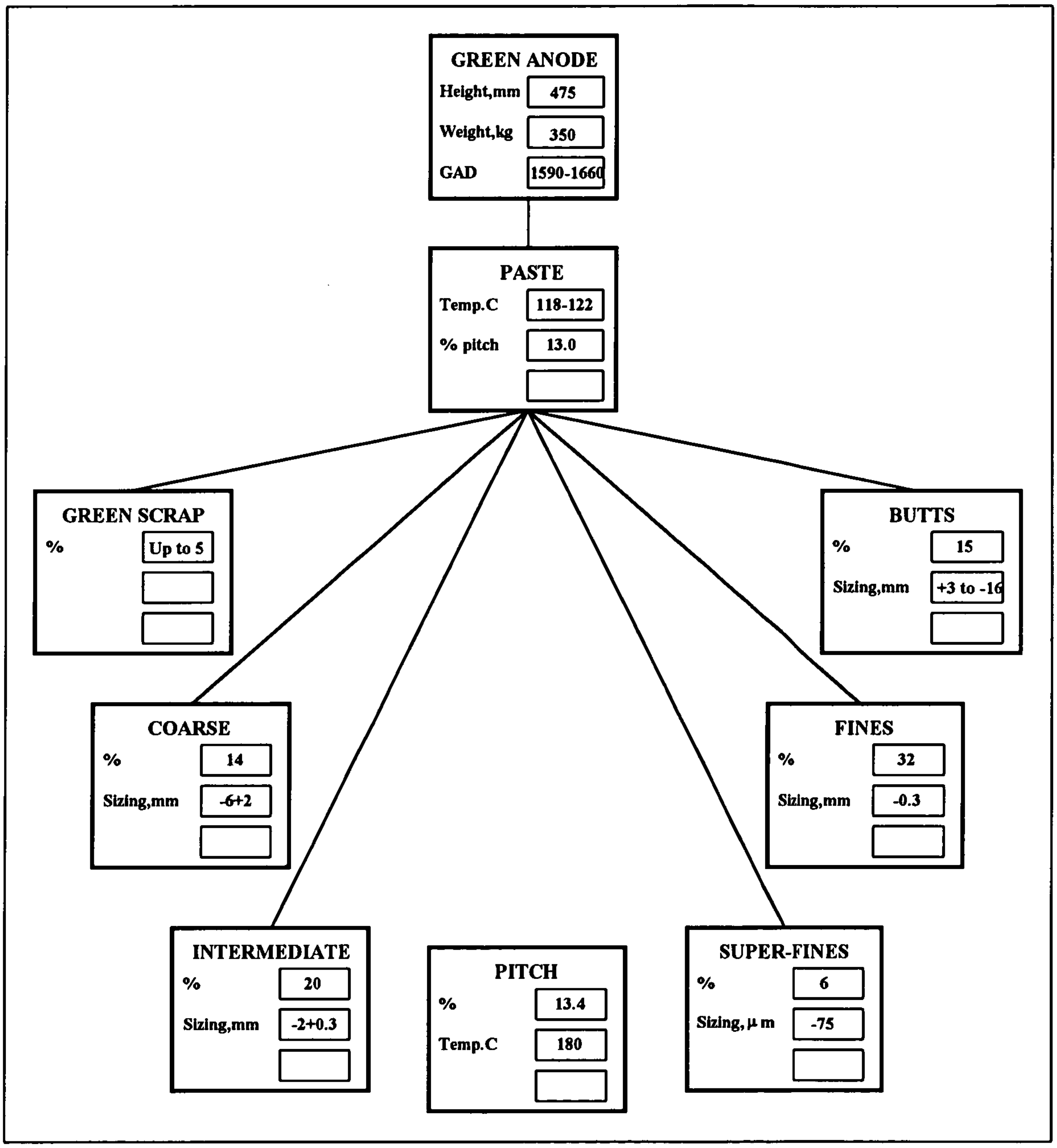


Figure 3.4: Green Anode Class

A schematic of the anode production process is shown in Figure 3.5. A mixer is emptied in turn every 12 minutes onto PB4 belt which feeds the paste into P2 Bin. Should there be a delay in emptying a mixer, the paste temperature is controlled by shutting valves on the HTO pipework to the respective mixer. The paste is conveyed from P2 Bin to the anode press via P3 belt. Since there is a temperature limitation of 200^{0}C on P3 belt, paste of a higher temperature than 200°C is scrapped by reversing PB4 belt and dumping into a small dump truck. Once the paste leaves the mixer, there is limited control over its rate of cooling.

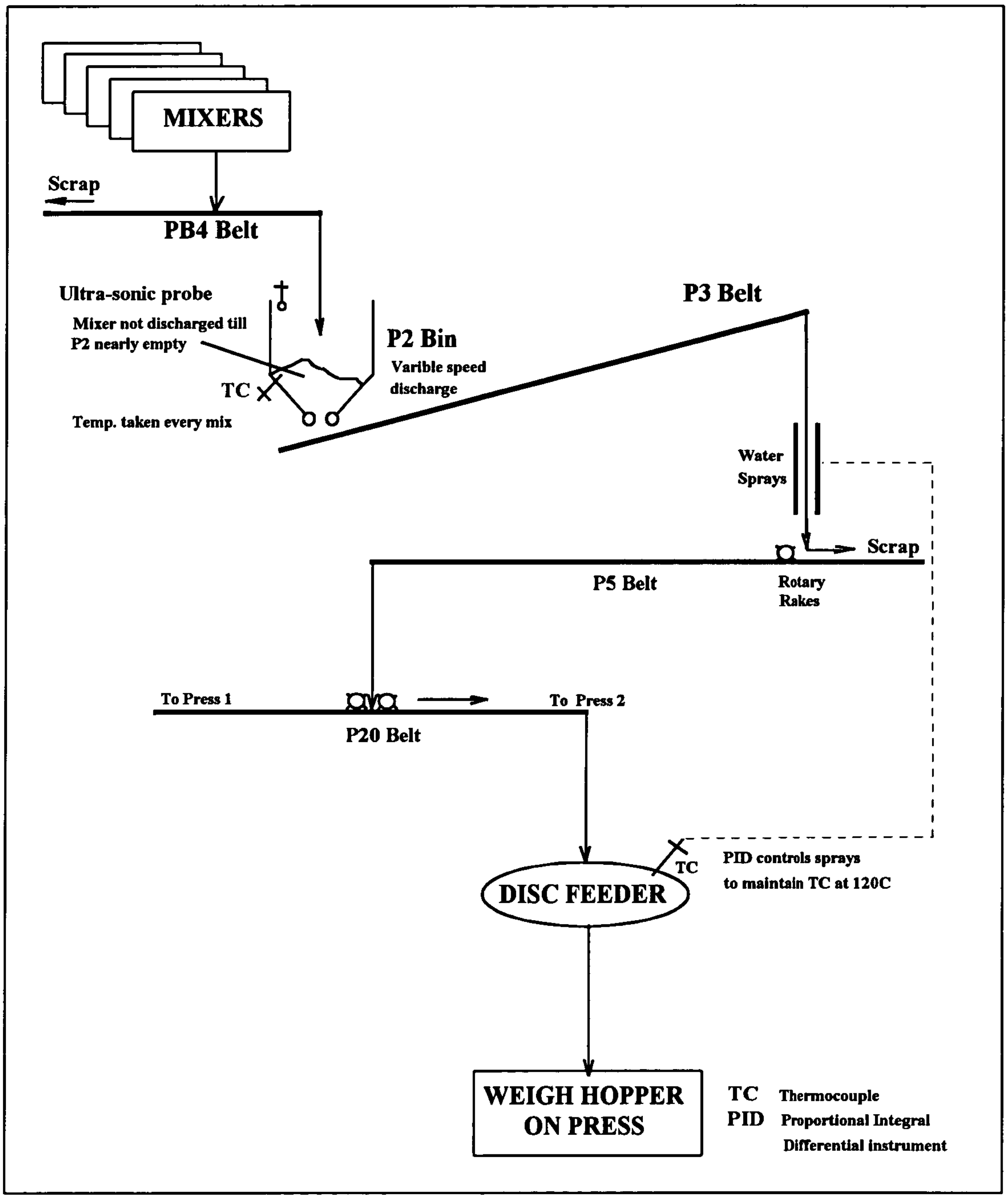


Figure 3.5: Schematic Diagram of the Anode Production Process

P3 is a long conveyor belt climbing 15m from ground level to the top of the presses and thence via several conveyors through water cooled air sprays to a disc feeder. The temperature of the paste measured at the disc feeder controls the cooling sprays to maintain this temperature to within 2°C of set point providing the temperature of the paste from the mixer is not too cool. The paste is fed into a batch weigher which discharges a mix into the press mould, where it is compressed into an anode at the rate of one every 60 seconds. On being ejected by the press it is weighed and its height recorded. Should the height lie outside set point limits, it is automatically sent to scrap for re-cycling. Anodes may also be rejected manually for various process reasons, such as being too weak or falling apart on the conveyor. Sound anodes are conveyed to storage or to the baking plant.

3.2.2 Ball Mill Problems

A schematic of the fines preparation circuit is shown in Figure 3.6. Fines are made by grinding coke in a ball mill, which process is very sensitive to changes in process variables. The Ball Mill is fed from a 12t feed bin containing the undersized material from a multi-stage screening process and from return oversize material from the ball mill operation itself. The mill is air-swept, with the air picking up dust particles and the dust laden air passing through a classifier. In the classifier, the dust is sorted into fines that meet the desired sizing and fines that is over-sized. The acceptable fines are passed to the fines storage bins while the over-sized fines are returned as ball mill feed.

Since the amount and sizing of the fines is one of the critical factors affecting the physical properties of an anode, two criteria have to be met:

- a product within a specified size range, of which Blaine Index is a measure,
- at a rate of 8t/h.

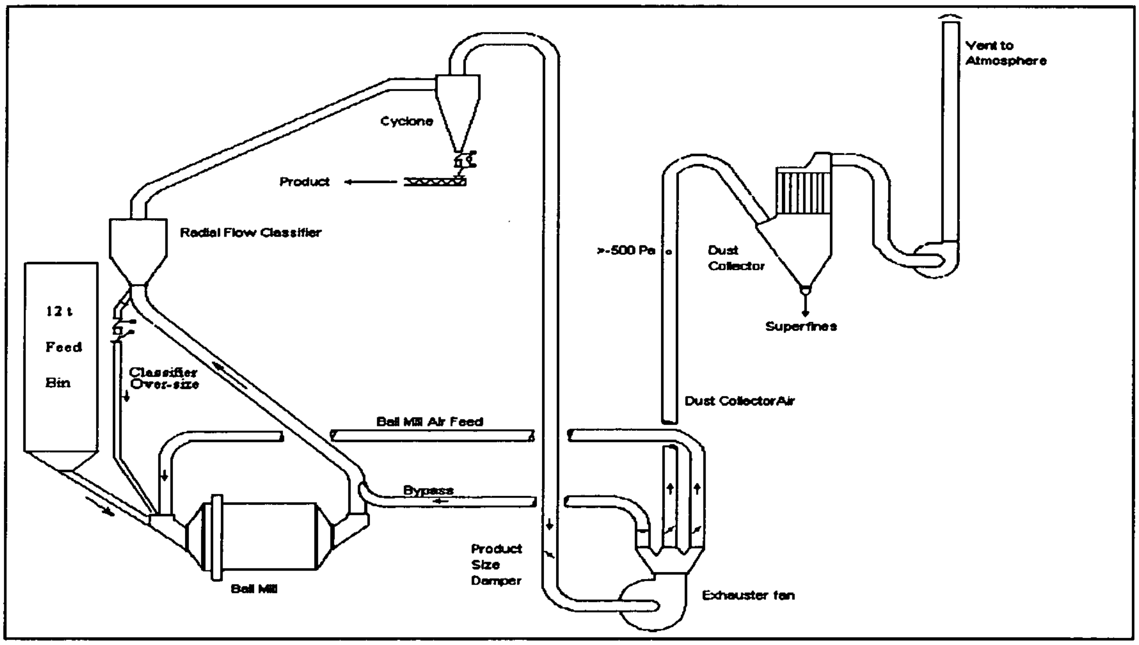


Figure 3.6: Schematic Diagram of the Fines Preparation Process

The value of the ball mill motor current provides a useful measure of the efficiency of the milling process. At optimum efficiency, the ball mill motor draws a current of between 300 and 320A. If the mill is over- or under-full, the ball mill motor current drops to below 300A and the product rate drops below 8t/h. The ball mill current, the feed bin level, the feed rate, the product rate and return feed rate are available as point values polled by the NIF server. The values of the Blaine Index are determined manually every four hours and keyed into the data base.

Some of the ball mill problems, causes and their solutions are depicted in Figure 3.7.

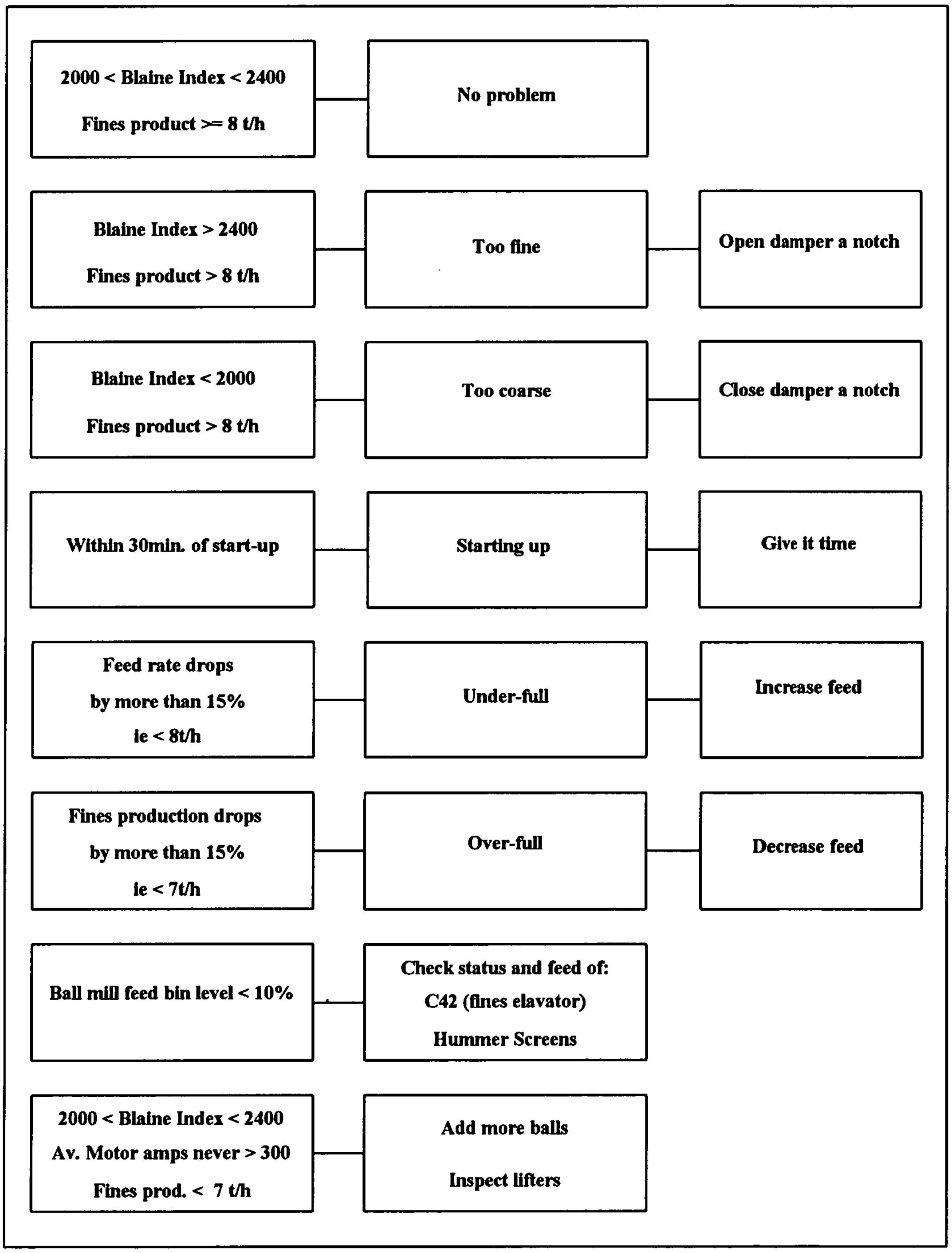


Figure 3.7: Schematic of Rules Relating to Ball Mill Operation

3.2.3 Mixer Paste Temperature Problems

A schematic diagram of the mixing process is shown in Figure 3.8. Coke aggregate and fines, called grist, and liquid pitch are fed into the top of the mixer. Heat transfer oil (HTO) is pumped from one of two HTO heaters around a ring main, returning back to the heater. The flow of HTO between the ring main and a mixer is controlled by a proportional flow control valve. Manual stop valves are used to isolate a mixer from the HTO circuit for maintenance. Hot oil flows around the mixer jacket and through the sigma paddles of each of five mixers and back to the ring main. Thermocouples register the temperature of the heat transfer oil at the HTO mixer inlet and outlet and of the paste in the mixer. The paste is mixed for about 50 minutes to attain a temperature of about 160°C before being discharged onto PB4 belt conveyor. The temperature of the paste entering the press mould has to be maintained within tight limits, else the anode will collapse or break up during conveyor transfer. Thus, the temperature in the mixer must be closely monitored and controlled. The temperature of the paste when it is discharged from the mixer is measured in P2 bin into which PB4 belt discharges.

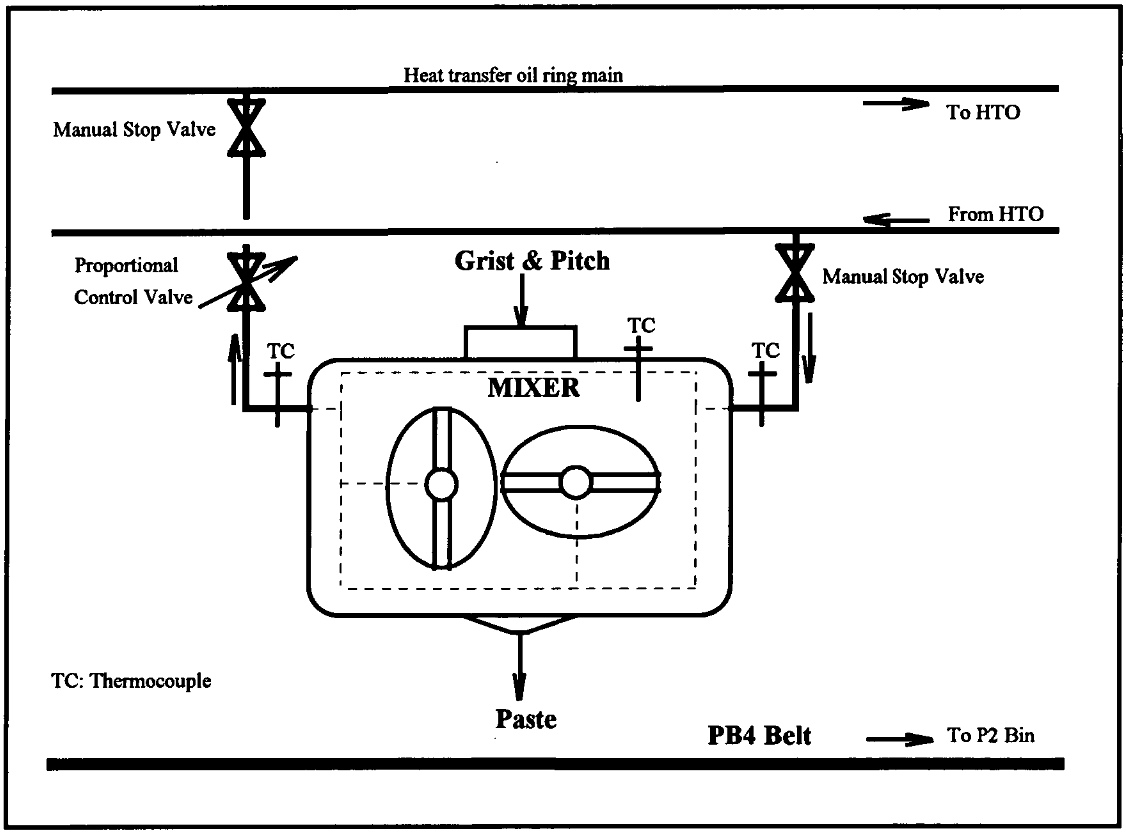


Figure 3.8: Schematic Diagram of the Mixing Process

Figures 3.9 and 3.10 show schematics of process parameters to check for the mixer paste being too cool or too hot respectively.

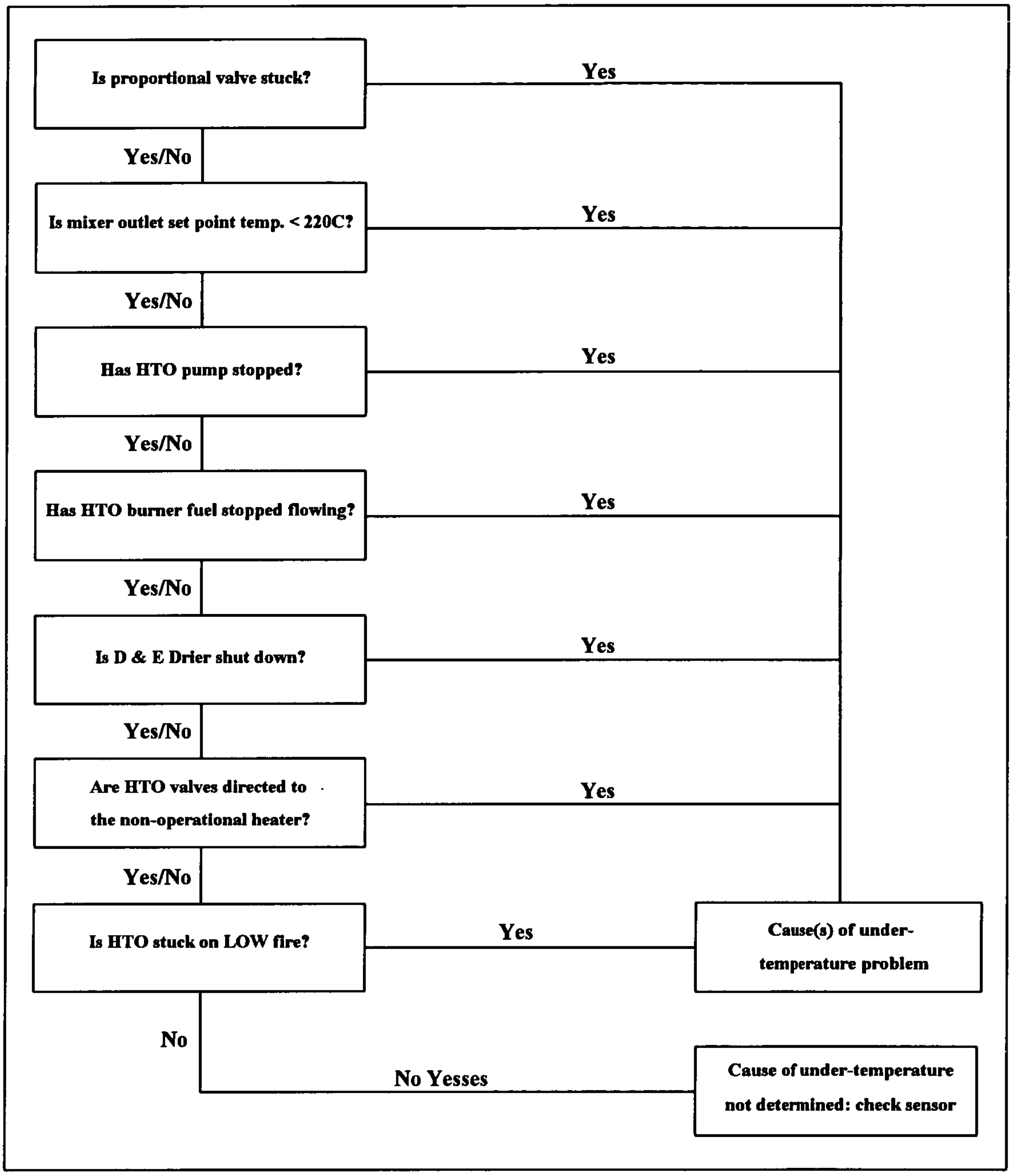


Figure 3.9: Schematic of Rules Relating to Mixer Paste Being Too Cool

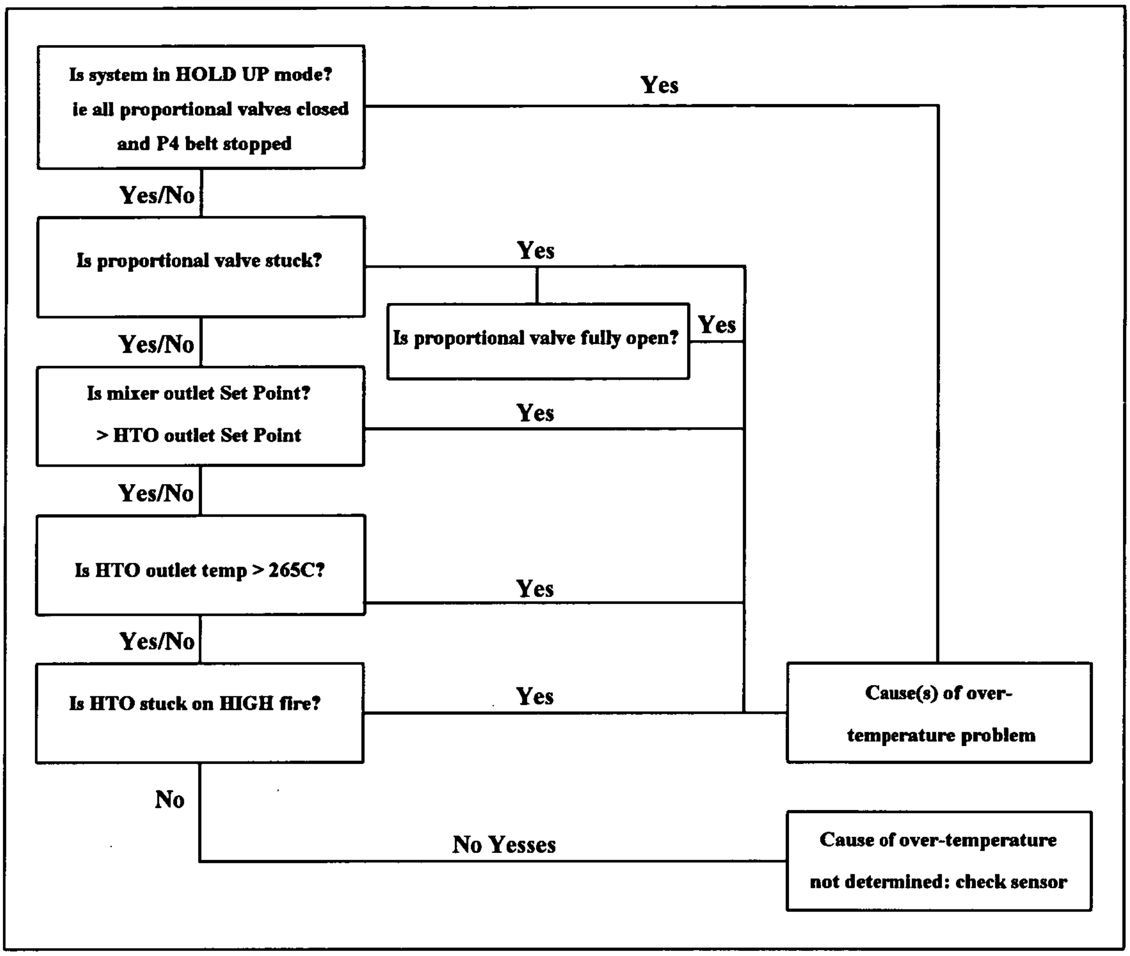


Figure 3.10: Schematic of Rules Relating to Mixer Paste Being Too Hot

3.2.4 Press Paste Temperature Problems

The hot paste is discharged from P2 bin through a variable speed feeder onto P3 belt conveyor that climbs from ground level to above the presses (refer to Figure 3.5). The paste loses some of its heat by natural convection in this five minute journey. On discharge from P3, the paste passes through water sprays onto two other belts before discharging onto a disc feeder that regulates the flow of paste into a weigher hopper on one of the two presses. On taring off at the set weight, the disc feeder stops and the weigh hopper empties into the press mould box. The press ram descends to compress the paste into a solid block. The ram then retracts and a lower ram rises to eject the block from the mould. The speed of the feeder on P2 bin is adjusted so that there is a smooth throughput of paste to match the output of anodes on a 60 second cycle. Should the cycle be interrupted, conveyors upstream of the press are stopped. The temperature of the paste entering the mould box is measured in the disc feeder and the flow of water and air to the cooling sprays regulated to maintain this temperature within tight limits of the set point. However, should the process be delayed excessively and the paste cool below the set point limit (there is no form of post-heating), then the paste is scrapped. Some of the reasons for the temperature of the paste entering the press mould being too high or too low are shown in Figures 3.11 and 3.12 respectively.

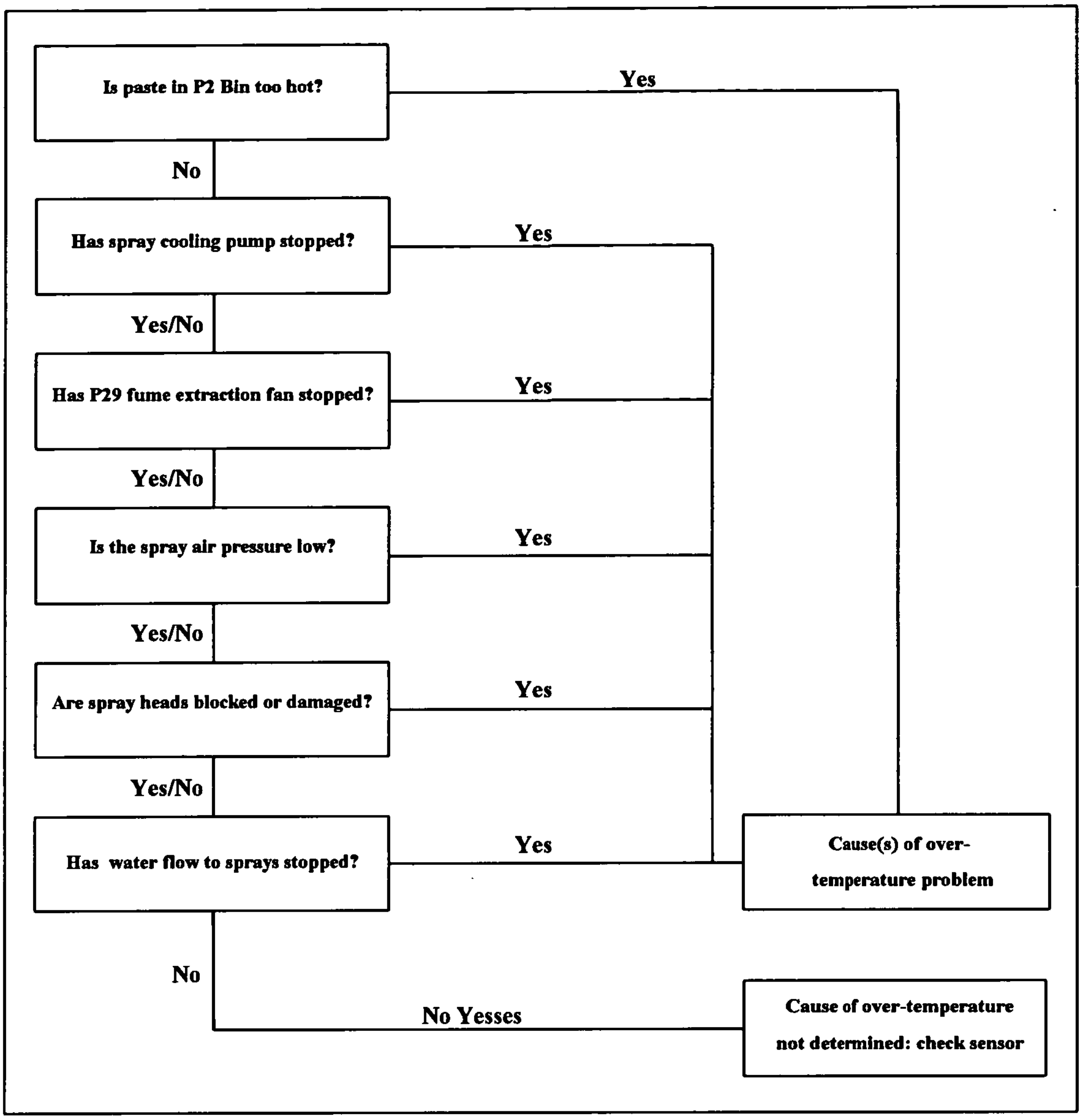


Figure 3.11: Schematic of Rules Relating to Paste Entering Press Being Too Hot

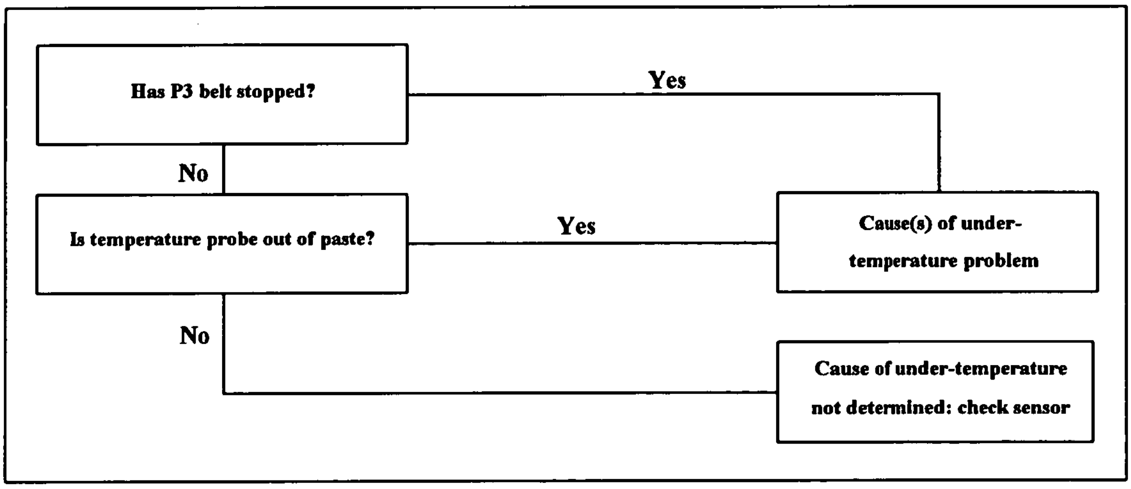


Figure 3.12: Schematic of Rules Relating to Paste Entering Press Being Too Cool

3.2.5 Statistical Analysis

The basis for this application is to analyse trends of data relating to each of the relevant process parameters. The trend line of a group of readings is obtained by applying the method of least squares. Thus, if data of a population is represented by:

X: $1, 2, 3, \ldots . n$
Y: $y_1, y_2, y_3 \ldots y_n$

Then, $\overline{X} = \dfrac{\sum X}{n}$ is the mean of X

$\overline{Y} = \dfrac{\sum Y}{n}$ is the mean of Y

$SS_X = \sum \left(X - \overline{X}\right)^2 = \sum X^2 - \dfrac{\left(\sum X\right)^2}{n}$ is the variation of X

$SS_Y = \sum \left(Y - \overline{Y}\right)^2 = \sum Y^2 - \dfrac{\left(\sum Y\right)^2}{n}$ is the variation of Y

$SP_{XY} = \sum \left(X - \overline{X}\right)\left(Y - \overline{Y}\right)$

$= \sum XY - \dfrac{\left(\sum X\right)\left(\sum Y\right)}{n}$ is the covariation between X and Y

and the equation of the trend line as represented by $\hat{Y} = a + b\hat{X}$

is derived from $b = \dfrac{SP_{XY}}{SS_X}$ and $a = \overline{Y} - b\overline{X}$

3.2.6 Hopper Weight, Anode Height and Weight Sensors

The weight of paste tared off by the weigh hopper (called the hopper weight) that discharges into the press mould box is recorded along with the resultant anode height and weight.

It is important that the anode height sensor is accurate as this determines those anodes that are automatically rejected to scrap. If the sensor is reading too low, then it will allow undersized anodes and may reject normal anodes. In fact, it has been found that re-calibrating the height sensor at the start of each shift is sufficient to avoid a problem in this area.

From a simplistic process view point, it is not so critical that the anode weight sensor is reading accurately. As long as the anode height is within acceptable limits there is no apparent process problem downstream. However, from a process analysis and control view point, it is important that the anode and hopper weight sensors also read accurately. Without accurate data, it is not possible to control the process within set limits. If the process cannot be controlled, then any improvements to the performance of an anode is ad hoc. On that basis, it is necessary to determine that a sensor is reading inaccurately and alert the operator to the need for its re-calibration.

Analysis of data for the three process variables - anode height, anode and hopper weights - determines trend lines of positive, negative or zero slope with respect to the upper and lower set point limits of each of the process variables. Possible trends are displayed in Figure 3.13.

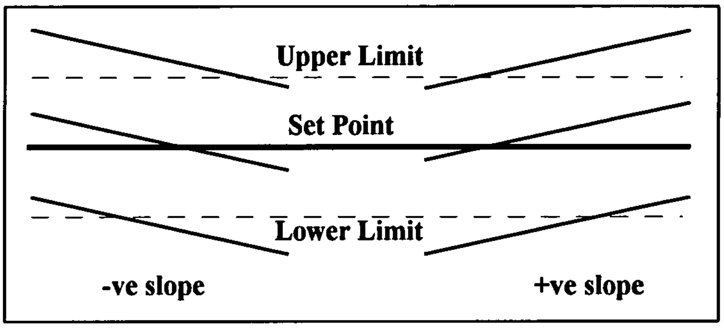


Figure 3.13: Trend Lines versus Process Limits

If a trend line indicates that the mean reading will stay within the set point limits for the next hour, then there is no problem. However, if a trend line indicates that the mean reading will be outside of these set point limits within an hour then there is a potential problem and further trend analysis is carried out.

This analysis is based on the relationship between the anode height, the anode weight and the paste weight. As the paste weight increases, so should the anode weight and anode height. Trend line slopes of different sign imply a sensor problem. Thus, a truth table, as shown in Table 3.2, can be compiled comparing possible trend line slopes of the three variables in order to arrive at a sensor or set point problem.

Theoretically, the hopper weight should be the same as the weight of the anode pressed from said paste. A difference between these two weights, called Δ(Weight) for convenience, outside a set limit indicates a problem with either the weigh hopper sensor and/or the anode weight sensor, as shown in the table. The most inaccurate of these two sensors is the one with a mean reading furthest from its set point.

If the mean of one or more of the three process variables is already outside its set point limits, then a trend analysis is not necessary as such. Instead, comparing the mean value of the Green Apparent Density (GAD is a function of the anode weight divided by its height) and the delta value with their respective set point limits indicates which of the sensors are in error. Thus, if the mean GAD is low and the mean Δ(Weight) less than its limit, then either the anode height sensor is reading high or both weight sensors are reading low. On the other hand, if the mean Δ(Weight) is greater than its limit, then it is most likely that the anode weight sensor is reading low.

	Sensor Reading Trend Slope				
Mean GAD	**Anode Weight**	**Hopper Weight**	**Anode Height**	**Δ Weight**	**Problem**
OK	+ve	+ve	+ve		Hopper weight set point
	-ve	-ve	-ve		Hopper weight set point
	+ve	-ve	+ve		Hopper weight sensor
	-ve	+ve	+ve		Anode weight sensor
	+ve	+ve	-ve		Anode height sensor
	-ve	-ve	+ve		Anode height sensor
	+ve	-ve	-ve		Anode weight sensor
	-ve	+ve	-ve		Hopper weight sensor
	Δ(Anode weight) > Δ(hopper weight)			> limit	Anode weight sensor
	Δ(Hopper weight) > Δ(anode weight)			> limit	Hopper weight sensor
Low				< limit	Anode height sensor reading high
				< limit	Both weight sensors reading low
				> limit	Anode weight sensor reading low
High				< limit	Anode height sensor reading low
				> limit	Anode weight sensor reading hig

* Δ(Weight) = | mean anode weight - mean hopper weight |
Δ(Anode weight) = | Mean anode weight - anode weight set point |
Δ(Hopper weight) = | Mean hopper weight - hopper weight set point |

Table 3.2: Truth Table for Anode Sensor Problems

It is possible that all three sensors are reading inaccurately to a greater or lesser degree. However, the purpose of the foregoing analysis is to determine the sensor most severely affected. Once so determined, that sensor can be re-calibrated and the analysis re-run to see if any of the other sensors require re-calibrating.

3.2.7 Statistical Process Control Charts

Three charts are used to present information regarding the performance of a process [Comalco 1996], namely, Shewhart, CUSUM and Exponentially Weighted Moving Average (EWMA) charts.

Shewhart Chart

If data of a population are represented by:

$$X: 1, 2, 3, \ldots n$$
$$Y: y_1, y_2, y_3 \ldots y_n$$

and this population is divided into sub-groups of size s such that:

P: $1, 2, 3, ..m$

Q: $q_1, q_2, ..q_i, ..q_m$

where, $m = n/s$ (+ 1 if there is a remainder to n/s)

and, q_1: $y_1, y_2, ..y_s$

q_2: $y_{s+1}, y_{s+2}, ...y_{2s}$

:

q_i: $y_{s(i-1)+1}, ...y_{iS}$

:

q_m: $y_{s(m-1)+1}, ...y_n$

then, $\overline{q_i} = \dfrac{\sum q_i}{s}$ is the mean of q_i

and, $\overline{Q} = \dfrac{\sum Q}{m}$ is the mean of Q

also, $\sigma = \sqrt{\dfrac{\sum (q_i - \overline{Q})^2}{m-1}}$ is the standard deviation of Q

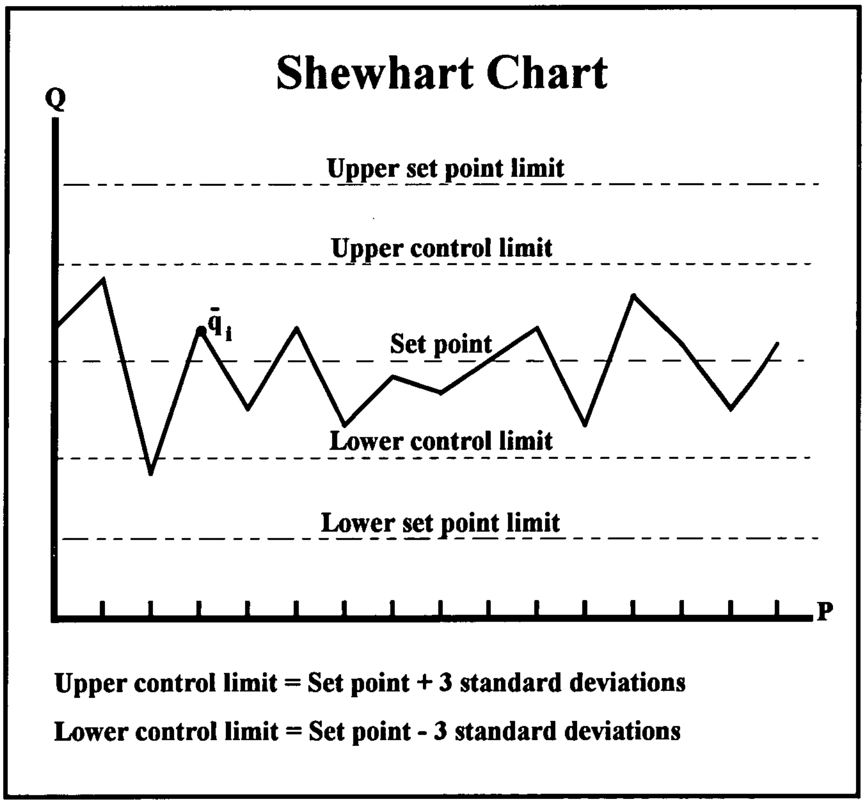


Figure 3.14: The Shewhart Chart

The Shewhart chart, depicted in Figure 3.14, displays the mean of q_i against the set point, its upper and lower limits and the upper and lower control limits. The set point is the target for a given process parameter with upper and lower set point limits as desirable process boundaries. The upper and lower control limits, equal to the set point plus or minus three standard deviations respectively, are an indication of how tight the process is being controlled.

CUSUM Chart

In the CUSUM chart, the cumulative sum of the variation from the set point of a population is plotted.

If data of a population are represented by:

X: $1, 2, 3, \ldots n$

Y: $y_1, y_2, y_3, \ldots y_n$

then, $S_i = \sum_{1}^{i}(y_i - Set\,Point)$ is the CUSUM at X = i.

However, even when the mean is on target, the CUSUM can wander far from zero, heralding a potential problem. To provide a means of deciding when a change is statistically significant, a mask is overlaid on the chart, as shown in Figure 3.15. The right hand end of the plot of S_i is the most recent reading of a population for a given process parameter. If this plot is not contained within the mask, then the process is out of control. The height of the narrow end of the mask is a user defined variable in the application program. This can be changed (made smaller) as the operators improve their control over the process.

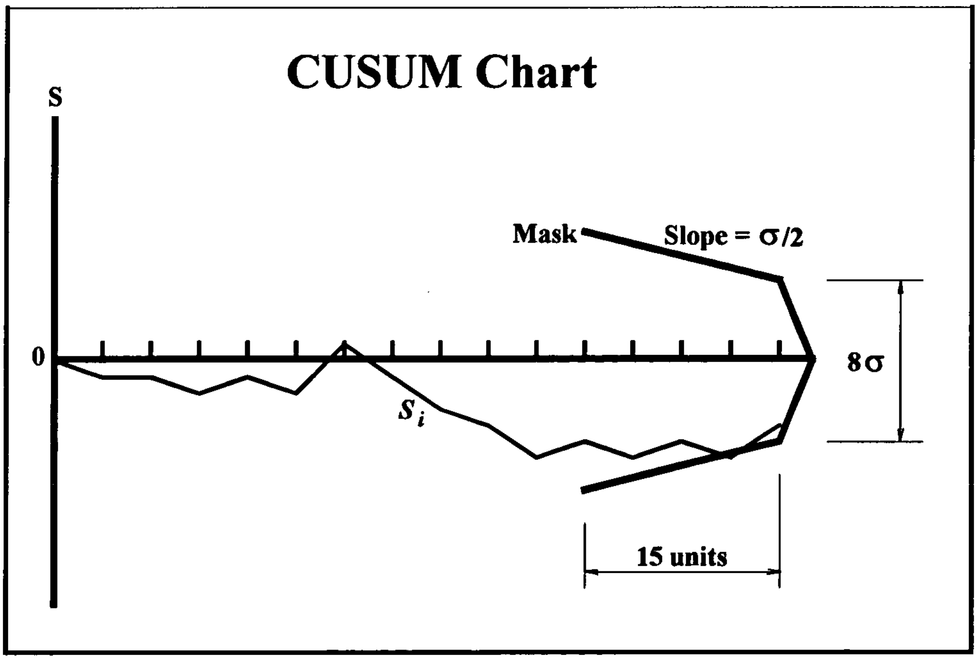


Figure 3.15: The CUSUM Chart

Exponentially Weighted Moving Average Chart

The Exponentially Weighted Moving Average (EWMA) chart, shown in Figure 3.16, is constructed so as to place more emphasis on recent observations and less on the values further back in a population series.

If data of a population are represented by:

X: *1, 2, 3, ...n*
Y: $y_1, y_2, y_3 \ldots y_n$

Then, $EWMA_1 = 0.4 \times y_1$

$$EWMA_2 = 0.4 \times y_2 + 0.6 \times 0.4 \times y_1 = 0.4 \times y_2 + 0.6 \times EWMA_1$$

$$\vdots$$

Thus, $EWMA_i = 0.4 y_i + 0.6 \times EWMA_{i-1}$

The upper and lower control limits = Set point $\pm 1.5 \times \sigma$ respectively, which is tighter than the control limits used in the Shewhart chart.

This chart is used to predict a trend, and due to the use of tight control limits, gives a clear indication of a process about to go out of control.

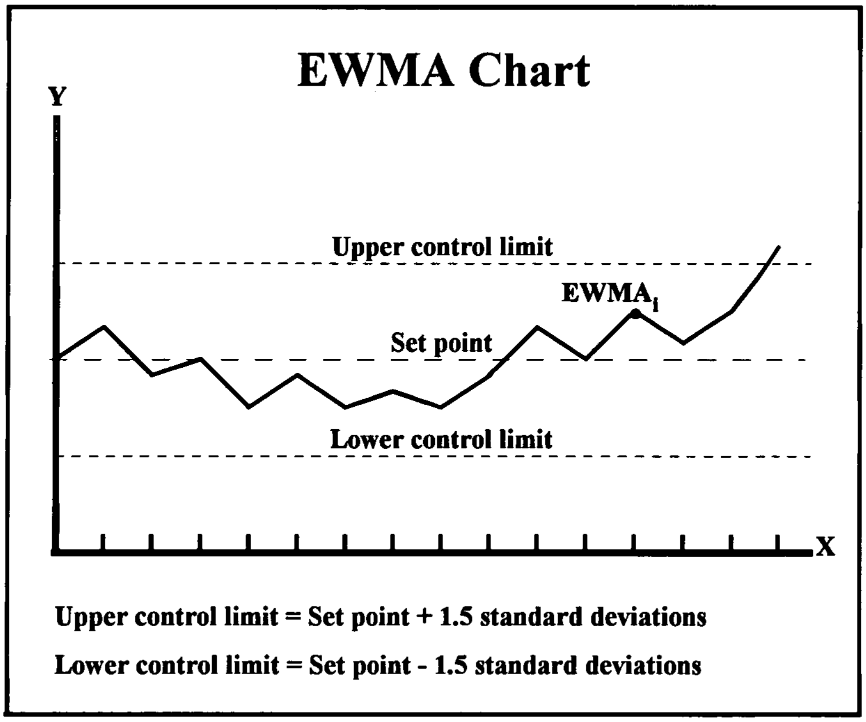


Figure 3.16: The Exponentially Weighted Moving Average Chart

3.2.8 Rules

The knowledge base formally sets out rules derived from the rule schematics shown in Figures 3.7 and 3.9 to 3.12 and truth table shown in Table 3.2. These rules are shown below.

- IF Current trend value > Set point upper limit
      OR Current trend value < Set point lower limit
  THEN Problem with sensor
      AND NOT Do sensor analysis

- IF (Current trend value > Set point upper limit
          AND Trend value > Set point upper limit in less than hour)
      OR (Trend value < Set point lower limit in less than hour
          AND Current trend value < Set point lower limit)
  THEN Do sensor analysis

- IF GAD trend OK AND Do sensor analysis
      AND (Anode weight trend positive
          AND Hopper weight trend positive
          AND Anode height trend positive)
      OR (Anode weight trend negative
          AND Hopper weight trend negative
          AND Anode height trend negative)
  THEN Problem with the hopper weight set point

- IF GAD trend OK AND Do sensor analysis
      AND Anode weight trend positive
      AND Hopper weight trend negative
      AND Anode height trend positive
  THEN Problem with the hopper weight sensor

- IF GAD trend OK AND Do sensor analysis
      AND Anode weight trend negative
      AND Hopper weight trend positive
      AND Anode height trend positive
  THEN Problem with the anode weight sensor

- IF GAD trend OK AND Do sensor analysis
      AND Anode weight trend positive
      AND Hopper weight trend positive
      AND Anode height trend negative
  THEN Problem with the anode height sensor

- IF GAD trend OK AND Do sensor analysis
  AND Anode weight trend negative
  AND Hopper weight trend negative
  AND Anode height trend positive
  THEN Problem with the anode height sensor

- IF GAD trend OK AND Do sensor analysis
  AND Anode weight trend positive
  AND Hopper weight trend negative
  AND Anode height trend negative
  THEN Problem with the anode weight sensor

- IF GAD trend OK AND Do sensor analysis
  AND Anode weight trend negative
  AND Hopper weight trend positive
  AND Anode height trend negative
  THEN Problem with the hopper weight sensor

- IF GAD trend OK AND Do sensor analysis
  AND Δ(Anode weight) > Δ(Hopper weight)
  AND Δ(Weight) > Δ(Weight) Limit
  THEN Problem with the anode weight sensor

- IF GAD trend OK AND Do sensor analysis
  AND Δ(Hopper weight) > Δ(Anode weight)
  AND Δ(Weight) > Δ(Weight) Limit
  THEN Problem with the hopper weight sensor

- IF GAD trend LOW AND Do sensor analysis
  AND Δ(Weight) < Δ(Weight) Limit
  THEN Anode height sensor reading high
  OR Both weight sensors reading low

- IF GAD trend Low AND Do sensor analysis
  AND Δ(Weight) > Δ(Weight) Limit
  THEN Anode weight sensor reading low

- IF GAD trend High AND Do sensor analysis
  AND Δ(Weight) < Δ(Weight) Limit
  THEN Anode height sensor reading low

- IF GAD trend High AND Do sensor analysis
  AND Δ(Weight) > Δ(Weight) Limit
  THEN Anode weight sensor reading high

- IF Blaine Index > 2400 AND Fines production > 8 t/h
  THEN Product too fine
  AND remedy IS "Open damper a notch"

- IF Blaine Index < 2000 AND Fines production > 8 t/h
  THEN Product too coarse
  AND remedy IS "Close damper a notch"

- IF Running time of Ball Mill < 30 min
  THEN Ball Mill starting up

- IF Ball Mill feed rate drop > 15%
  THEN Ball Mill underfull
  AND remedy IS "Increase feed"

- IF Ball Mill fines production drop > 15%
  THEN Ball Mill overfull
  AND remedy IS "Decrease feed"

- IF Ball Mill feed bin level < 10%
  THEN Ball Mill feed bin nearly empty
  AND check status and feed of fines elevator and Hummer screens

- IF Blaine Index > 2000 AND Blaine Index < 2400
  AND Average Ball Mill motor amps never > 300
  AND Fines production < 7 t/h
  THEN Low on balls AND inspect lifters

- IF paste temperature in Mixer # is low
  AND Proportional valve stuck
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS proportional valve stuck

- IF paste temperature in Mixer # is low
  AND Mixer outlet set point temp < 220°C
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS low mixer outlet set point temp

- IF paste temperature in Mixer # is low
  AND HTO Pump not running
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS HTO pump not running

- IF paste temperature in Mixer # is low
  AND HTO burner fuel not flowing
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS HTO burner fuel not flowing

- IF paste temperature in Mixer # is low
  AND D & E Drier not running
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS D & E Drier not running

- IF paste temperature in Mixer # is low
  AND HTO valves not directed to operational heater
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS HTO valves incorrectly set

- IF paste temperature in Mixer # is low
  AND HTO valves stuck on LOW fire
  THEN Low mixer paste temp problem found
  AND Low mixer paste temp problem IS HTO valves stuck on LOW fire

- IF paste temperature in Mixer # is low
  AND NOT Low mixer paste temp problem found
  THEN Cause of low mixer paste temp problem not found

- IF All proportional valves are closed
  AND PB4 belt stopped
  THEN System in HOLD-UP mode

- IF paste temperature in Mixer # is high
  AND System in HOLD-UP mode
  THEN High mixer paste temp problem found
  AND High mixer paste temp problem IS system in HOLD-UP mode

- IF paste temperature in Mixer # is high
  AND Proportional valve stuck
  THEN High mixer paste temp problem found
  AND High mixer paste temp problem IS proportional valve stuck

- IF paste temperature in Mixer # is high
  AND Mixer outlet set point temp > HTO outlet set point
  THEN High mixer paste temp problem found
  AND High mixer paste temp problem IS high mixer outlet set point temp

- IF paste temperature in Mixer # is high
  AND HTO outlet temp > 265°C
  THEN High mixer paste temp problem found
  AND High mixer paste temp problem IS high HTO outlet temp

- IF paste temperature in Mixer # is high
  AND HTO stuck on HIGH fire
  THEN High mixer paste temp problem found
  AND High mixer paste temp problem IS HTO stuck on HIGH fire

- IF paste temperature in Mixer # is high
  AND NOT High mixer paste temp problem found
  THEN Cause of high mixer paste temp problem not found

- IF Paste temperature in Press is high
  AND Paste in P2 bin too hot
  THEN High press paste temp problem found
  AND High press paste problem IS mixer paste too hot

- IF Paste temperature in Press is high
  AND water spray pump not running
  THEN High press paste temp problem found
  AND High press paste problem IS water spray pump not running

- IF Paste temperature in Press is high
  AND spray air pressure low
  THEN High press paste temp problem found
  AND High press paste problem IS spray air pressure low

- IF Paste temperature in Press is high
  AND NOT High press paste temp problem found
  THEN Operator to check spray heads are not blocked or damaged
  AND Operator to check water flow to sprays
  ELSE Cause high press paste temp problem not found

- IF Paste temperature in Press is low
  AND P3 belt stopped
  THEN Low press paste temp problem found
  AND Low press paste problem IS P3 belt stopped

- IF Paste temperature in Press is low
  AND NOT Low press paste temp problem found
  THEN Operator to check temperature probe in paste in disc feeder
  ELSE Cause of low press paste temp problem not found

3.3 The Data Base

As its name implies, the data base contains all the factual data required to solve the problem being tackled. It may contain unchanging data relating to the problem, data that may need changing occasionally for the purpose of controlling the way the application runs and current data that is changing dynamically. It is useful to be able to change the application's control parameters external to the application without accessing the coding of the expert system. This could be done through the user interface or through an external (to the application) data base such as Microsoft Access or Focus.

Current data could be input from an external source, directly by the user via the keyboard or by the expert system itself as it fires rules that causes data values to change. Data that is changing dynamically could be read directly into the expert system application or read into an intermediate system such as Microsoft Excel that in turn is read by the application. If the data is changing more rapidly than it can be processed, since time is required to read that data into the application and process it, then a problem arises that requires special consideration.

The process monitor uses three types of process parameters:

- process variables stored in the SCADA Access database,
- instantaneous point values obtained through the Network Interrogation Facility (NIF) server and stored in an Excel file,
- parameters that affect the running of the process monitor and input by the user into an Access file.

Three tables are referenced in the SCADA Access database, namely, *g_sieve, gc_batch* and *gc_anode.* The fields accessed, using the descriptive name rather than the field name, are listed in Table 3.3.

G_SIEVE	GC_BATCH	GC_ANODE
Most recent value:	Values in past 2 hours:	Values in past 2 hours:
Blaine Index	Date & Time Stamp (DTS)	Date & Time Stamp (DTS)
	Coarse	Anode weight
	Fines	Anode height
	Butts	Paste temperature
	Intermediate size	Paste weight
	Super fines	Max. press pressure
	Pitch	
	P2 temperature	
	Mixer number	

Table 3.3: Tables Referenced in SCADA Database

The second type of process variable are the instantaneous point values polled by the NIF server, where a point value is the value of a specific attribute, eg direction of conveyor, pump ON/OFF, anode weigh and height set points, paste temperature, percentage closure of valve, etc. The point values used are listed in Table 3.4.

Mixer		Mixer #1	Mixer #2	Mixer #3	Mixer #4	Mixer #5
Mixer motor current	Point ID	MXIT16	MXIT17	MXIT18	MXIT19	MXIT20
	Range	0-150amp				
Proportional valve	Point ID	MXFV21	MXFV22	MXFV23	MXFV24	MXFV25
	Range	0-100%				
Mixer HTO outlet temp SP	Point ID	MXTT2SP	MXTT4SP	MXTT6SP	MXTT8SP	MXTT10SP
	Range	0-300C				
Pitch level	Point ID	LPMX001SP	LPMX002SP	LPMX003SP	LPMX004SP	LPMX005SP
	Range	0-1000%				
HTO		**HTO #1**	**HTO #2**			
HTO outlet temp Set Point	Point ID	HOHT01SP	HOHT02SP			
	Range	0-300C				
Outlet temperature	Point ID	HOTT6	HOTT8			
	Range	0-300C				
Hot oil circulating pump	Point ID	HOPUH01S	HOPUH10S			
	Range	0,1,2	OFF, ON, Overload			
Oil flow to HTO burner	Point ID	HOFT10				
	Range	0-20000l/h				
P2 & Presses		**Press #1**	**Press #2**			
Weight control Set Point	Point ID	ACPR1WTSP	ACPR2WTSP			
	Range	0-400kg				
Height control Set Point	Point ID	ACPR1HTSP	ACPR2HTSP			
	Range	300-500mm				
Minimum P2 temperature	Point ID	P2MINTMPSP				
	Range	0-200C				
Maximum P2 temperature	Point ID	P2MAXTMPSP				
	Range	0-200C				
Water spray Set Point	Point ID	PCSPRAY1SP				
	Range	0-200C				
Water spray pump motor	Point ID	ACIT14				
	Range	40-60Hz				
Ball Mill						
Fines Bins total	Point ID	BMLTFINE				
	Range	0-400%				
C46 Feed mass flow	Point ID	BMFIT1				
	Range	0-25t/h				
C45A Return mass flow	Point ID	BMFIT5				
	Range	0-20t/h				
C49 Product mass flow	Point ID	BMFIT6				
	Range	0-20t/h				
C46 BM motor current	Point ID	BMIT12				
	Range	0-400amp				
12t Feed bin	Point ID	CPLT20				
	Range	0-100%				
C42 Bucket elevator status	Point ID	CPBEC42S				
	Range	0-7	OFF, ON, Overload, Underspeed			
C64/2 Hummer screen motor 1 status	Point ID	CPVSC642S1				
	Range	0,1,2	OFF, ON, Overload			
C64/2 Hummer screen motor 2 status	Point ID	CPVSC642S2				
	Range	0,1,2	OFF, ON, Overload			
C64/2 Hummer screen motor 3 status	Point ID	CPVSC642S3				
	Range	0,1,2	OFF, ON, Overload			
Other						
P3 Conveyor belt	Point ID	PCBCP3S				
	Range	0,1,2	OFF, ON, Overload			
C20 D&E Drier	Point ID	CDDRC20S				
	Range	0,1,2	OFF, ON, Overload			
Mixing plant air pressure	Point ID	MXPT1				
	Range	0-150psi				
P20 Paste conveyor direction	Point ID	PCBCP20D				
	Range	0,1,2	Off, Forward, Reverse			

Table 3.4: List of Point ID's and Ranges Accessed by the NIF Server

Table 3.4 lists for each point value accessed, its description, its point ID and the range as an absolute value, a percentage or a value state. For instance, *Mixer #1 motor current*, has a point ID of *MXIT16* and can have a value in the range of *0-150amp*, while *P20 paste conveyor* has a point ID of *PCBCP20D* with three values, *0, 1* and *2* representing *Off, Forward* and *Reverse*. The point ID's are used by the SCADA control system to address the point values. They can also be used by external programs such as Excel and other Application Program Interfaces (API's). In this instance, the point values are linked to an Excel file *NIFserve.xls* which in turn is read by the process monitor.

The third type of process variable are those that are not available as point values, or those that provide flexibility in the way the process monitor runs. Values are input by the user in table *AnodeLimit* in Access file *pressdat.mdb*. Table 3.5 defines the database fields used for the appropriate process and application parameters and the table of the actual values used is shown in Appendix Table 3.4 in Appendix 3.

db Field	Field Description
Set_Point	Set point unobtainable through NIF server
SP_Limit_Width	Difference between set point and upper or lower limit
WarnDeltaValue	Difference between set point and warning limit
AlarmValue	Absolute value for an alarm
Err_LowLmt	Values below this limit are erroneous
Err_UppLmt	Values above this limit are erroneous
Reading_Span	Readings analysed in period prior to NOW
Value	A value relating to the process or application parameter
P1_GAD_Ht_Const	For press 1: 'a' in GAD = Weight/(a.Height + b)
P1_GAD_Const	For press 1: 'b' in GAD = Weight/(a.Height + b)
P2_GAD_Ht_Const	For press 2: 'a' in GAD = Weight/(a.Height + b)
P2_GAD_Const	For press 2: 'b' in GAD = Weight/(a.Height + b)
Mask_Height	Height of mask at narrow end in CUSUM chart

Table 3.5: Field Descriptions used in Database Table *AnodeLimit*

The process variables analysed and trended are: mixer paste (P2) temperature, percentage pitch, paste in hopper weight (called hopper weight), press paste temperature, anode weight, anode height and press pressure. From these variables are generated two more variables, anode weight minus hopper weight and Green Apparent Density, that provide further information about the process. The basic data for the statistical analysis of these nine variables are obtained from data generated in the two hours (a user input variable in the db field 'Reading_Span') prior to running the application through an analysis cycle and extracted from the *gc_batch* and *gc_anode* tables in the SCADA database. The operation of the Ball Mill is also analysed, using the most recent value of Blaine Index from the *g_sieve* table and data obtained in prior analysis of some of the other process variables. If a problem is detected in any of these analyses, an endeavour is made to ascertain the cause by examining the point values obtained through the NIF server and stored in the Excel file, *NIFserve.xls*.

3.4 The Developed Process Monitor

Previous sections have discussed the anode production process in detail and the interactions between the operator and that process through the SCADA system. The need for a means of further monitoring the process has been raised and the method of providing that operator aid addressed. The rule base and data base of the required expert system has been established and it now remains to describe the program structure of this process monitor. The various aspects of this relationship are shown diagrammatically in Figure 3.17.

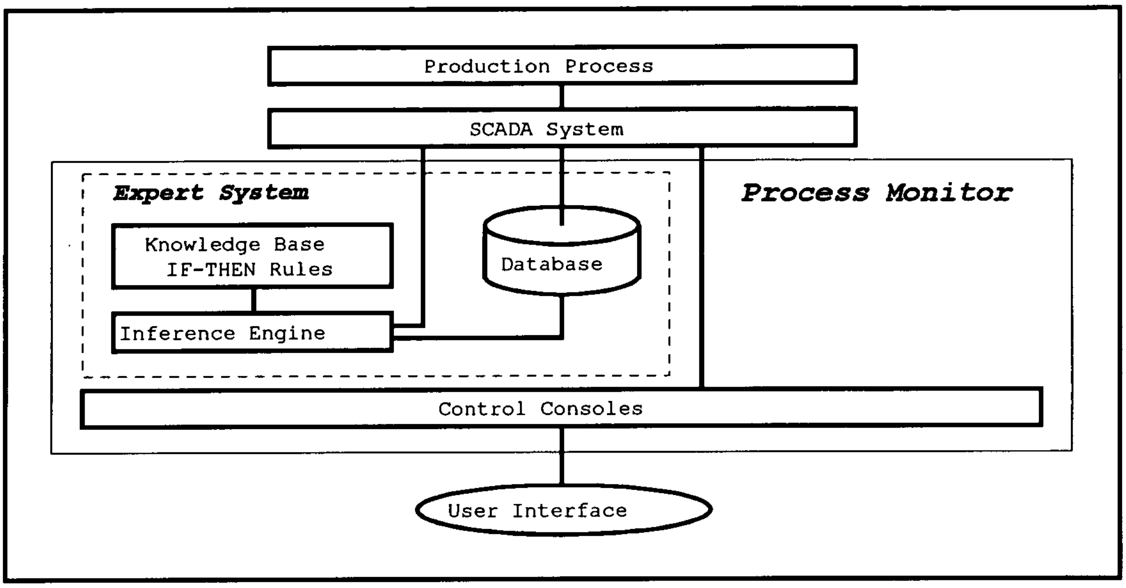


Figure 3.17: Relationship between the Process Monitor and the Process

3.4.1 Program Structure

The program structure of the developed process monitor, *monitor.knb*, is based on the following functions, namely:

- Carry out an analysis of each of the process variables.
- From the analysis, identify problems in the anode production process.
- Determine the cause of the problem.
- Provide a solution to any problem found.
- Display statistical process control charts and informational messages.

The process variables analysed are: mixer paste (P2) temperature, percentage pitch, hopper weight, press paste temperature, anode weight, anode height and press pressure. If the plant is running properly, there are 15 values for each of the first two variables and in excess of 100 for each of the remaining variables in a reading span of two hours. From these variables are generated two other variables, anode weight minus hopper weight and Green Apparent Density, that provide further information about the process. Also analysed is the operation of the Ball Mill.

The general program structure and flow is depicted in Figure 3.18. Object oriented techniques are used where possible to avoid duplication of program code. Related properties and attributes are grouped together in classes of varying size, as listed in Appendix 2.

The first module involves getting the data from SCADA and from the user table in Microsoft Access. If some of the data links are broken, or there is insufficient data to analyse as occurs in the start up and shut down phases, or production has ceased altogether, then a message is displayed in the summary table to indicate the reason why analysis cannot be carried out and which link(s) is broken, if applicable. The application bypasses the analysis modules and continues to cycle every five minutes, interrogating SCADA and the databases, until the link(s) are restored or until production resumes.

For a given variable (excluding that for the Ball Mill), a statistical analysis is carried out, as described in Section 3.2.5. From this analysis, it is determined if there is a problem with the process. If a potential problem is detected arising from analysis of the anode weight, or anode height or hopper weight readings, then an analysis of the respective sensors is carried out as described in Section 3.2.6. If a potential problem is detected with the paste or mixer temperatures then the point values are examined to determine the cause.

The process control charts are displayed and messages relating to the analysis displayed below the chart. These messages are also sent to the table *mess_text* in the user database *pressdat.mdb* for later retrieval if required. The charts and accompanying messages remain on the screen for 30 seconds (a user input variable), which feature can be overwritten by the user clicking on a push-button to hold the existing display for further study or printing. The hold is overwritten by clicking a push-button to continue, or by default after 5 minutes. Each of the nine process variables are dealt with in turn in this manner.

In the case of the Ball Mill, a trend analysis is not carried out since the process does not change rapidly. For optimal performance two criteria have to be met, namely, fines production of 8t/h sized with a Blaine Index value between 2000 and 2400. The Blaine Index should be measured every 4 hours. The product rate can be obtained from the point value, *BMFIT6* of the product rate mass flow device. However, readings obtained from the mass flow devices for fines product rate, feed rate and return feed rate are notoriously inaccurate. Sometimes the reading for the fines product rate is 20t/h against a design rating for the mill of 8t/h. The actual, as distinct from measured, fines product rate is arrived at by:

calculating the percentage fines discharged into the mixers (derived from table *gc_batch*) in the span of readings (derived from the start and finish DTS's),

multiplying that percentage by the weight of anodes (derived from table *gc_anode*) made in the span of readings,

to arrived at the fines used, and

adding the amount of fines put into, minus if removed from, the four 12t fines storage bins (derived from the difference in bin level over a 100 minute period, values for which are stored in *NIFserve.xls*).

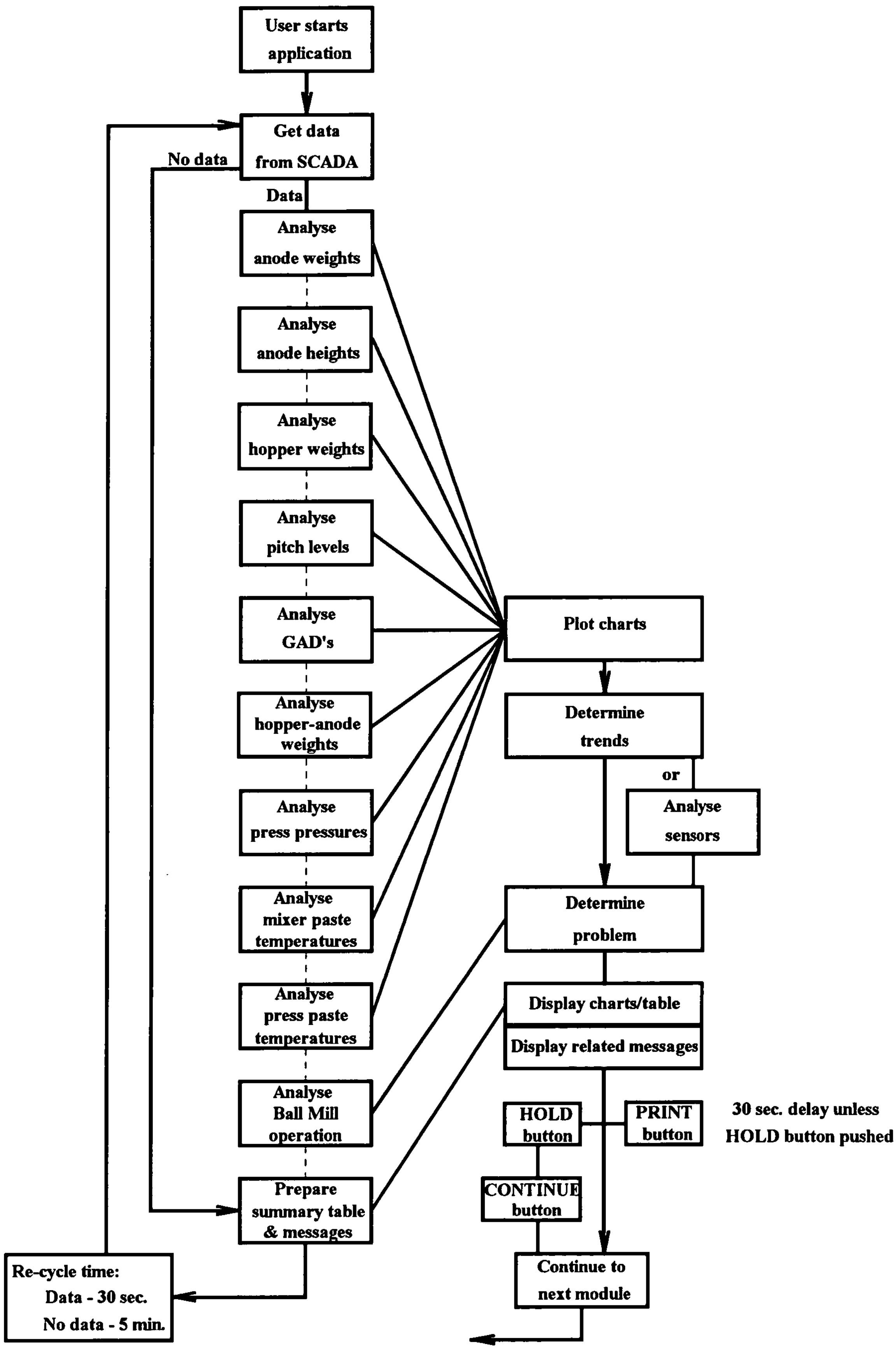


Figure 3.18: Program Structure of Process Monitor

If the Blaine Index is outside the limits and/or the calculated product rate below 7t/h, then the cause of the problem is sought as per Figure 3.7. Informational messages relate to the problem, the motor amps, the Blaine Index and when it was last measured, the feed and fines bins levels and the accuracy of the mass flow devices.

At the conclusion of this trend analysis phase, a summary table is displayed showing key data, any problems and their cause. A message table is also displayed which can be scrolled through to view the last two hours of messages. The whole cycle takes about ten minutes, after which the cycle repeats itself with the SCADA database being accessed again to collect the most recent data.

3.4.2 Analysis of Data and Trends

Current data for each of the process variables are read from the SCADA database into the application. For example, data relating to all the anodes produced during the reading span are read into the Class *Green Anode*, with an instance created dynamically for each anode. Thus, instance *Green Anode 1* has related values for the first anode sampled in the reading span for each attribute, *Height, Weight, Hopper_wt, Pr_temp, Max_press* and *DTS.* Similarly, data for the second anode is stored against *Green Anode 2* and so on. Calculated attributes are added to each of the instances, and used in the plotting of the three charts.

In Section 3.2.5, the method of calculating the mean and trend line of a population of readings is set out. If the mean is contained between the upper and lower set point limits, then the time taken for the trend to break either of these limits is calculated. If this time is less than one hour, then a message is generated to that affect. In this way, the operator is forewarned that a problem is developing.

Informational messages regarding trending take the form set out below, where *Property* relates to the process variable being analysed and current value is the most recent value as defined by the trend line.

- Mean *Property* is *X units* with trend of change = *Y units*/hr.
- *Property* trend steady between Set Point limits.
- Current value of *Property* is just below the upper Set Point limit
- *Property* trend decreasing. May fall below Set Point lower limit within an hour.
- Current value of *Property* is just above the lower Set Point limit.
- *Property* trend increasing. May rise above Set Point upper limit within an hour.
- *Property* above the Set Point limit, though steady.
- Trend of high *Property* to come in limits within an hour.
- *Property* above Set Point upper limit with trend increasing further.
- *Property* below Set Point lower limit, though steady.
- Trend of low *Property* to come in limits within an hour.
- *Property* below Set Point lower limit with trend decreasing further.

Limiting values are defined in Figure 3.19, though the ALARM category is only used in relation to the paste temperatures. Readings that are obviously erroneous are defined in the *AnodeLimit* table in the database *pressdat.mdb*, either as absolute values or as a ratio of the variable's set point. Generally, a variable's value is deemed erroneous if it differs from its set point by more than 10%. Appendix Table 3.4 shows the current limiting values. The occasional reading that is deemed erroneous for being too high or low is assigned the mean value of the previous group of readings for the purpose of statistical analysis. Where the number of erroneous readings exceeds 10% of the total number of readings for a given variable, then it is obvious that the sensor giving rise to those readings is seriously in error. This is particularly true of the anode weight sensor which is subject to impact loading and quickly drifts out of calibration, sometimes by as much as 100kg.

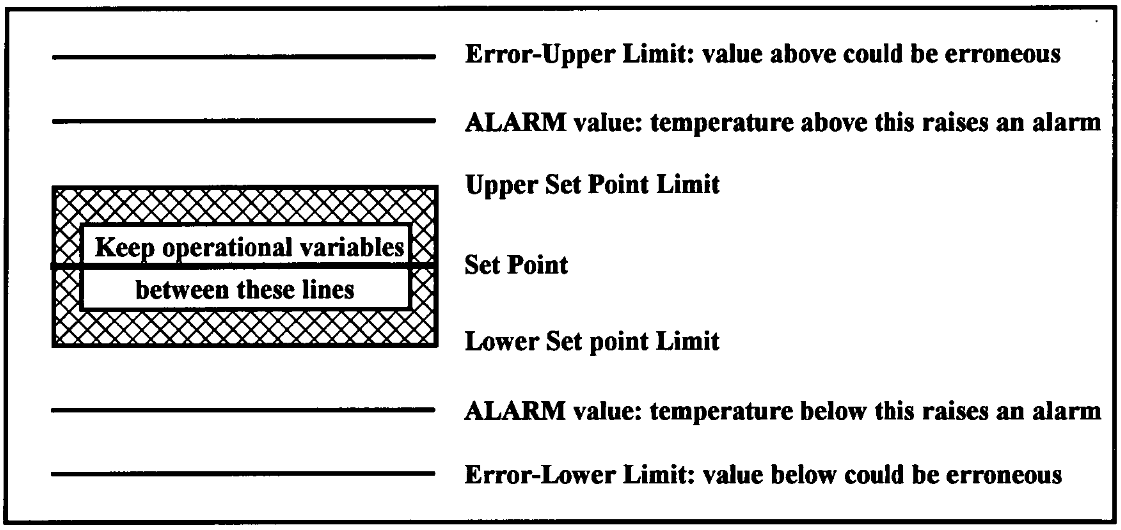


Figure 3.19: Definition of Limiting Values

Another example of an erroneous value is that of a press paste temperature reading of less than 110°C being recorded. This can occur when the disc feeder is empty of paste and the probe is merely measuring the air temperature. In this case, the temperature is plotted as 112°C, but given a value equal to the mean of the previous group of readings for the purpose of statistical analysis.

If the mean or current value is outside the set point limits then a problem exists.

3.4.3 Determination of a Problem

The program determines the existence of a problem in a manner depicted in Figure 3.20 based on an analysis of the read from the SCADA database.

The trend analysis indicates either no problem, a potential problem within an hour unless corrective action is taken or an immediate problem. In the first instance no message is displayed. In the case of a potential problem involving one of the weight or height sensors, the analysis will indicate which sensor or set point is most likely to be drifting and display a message accordingly.

For an immediate problem, the fault might be obvious if involving a height or weight sensor, or might necessitate interrogating SCADA for further data, which search might not find a cause. In any event, a message is displayed noting the findings.

Should the cause of a problem be determined, the hypertext legend "*Click for SOP*" appears in red. Clicking on this brings up a second screen on which is displayed the relevant Standard Operating Procedure (SOP) setting out the method of fixing the problem. This SOP can be viewed or printed. Each SOP is written in a text file separate from Level5 Object to permit easy maintenance of the SOP text files.

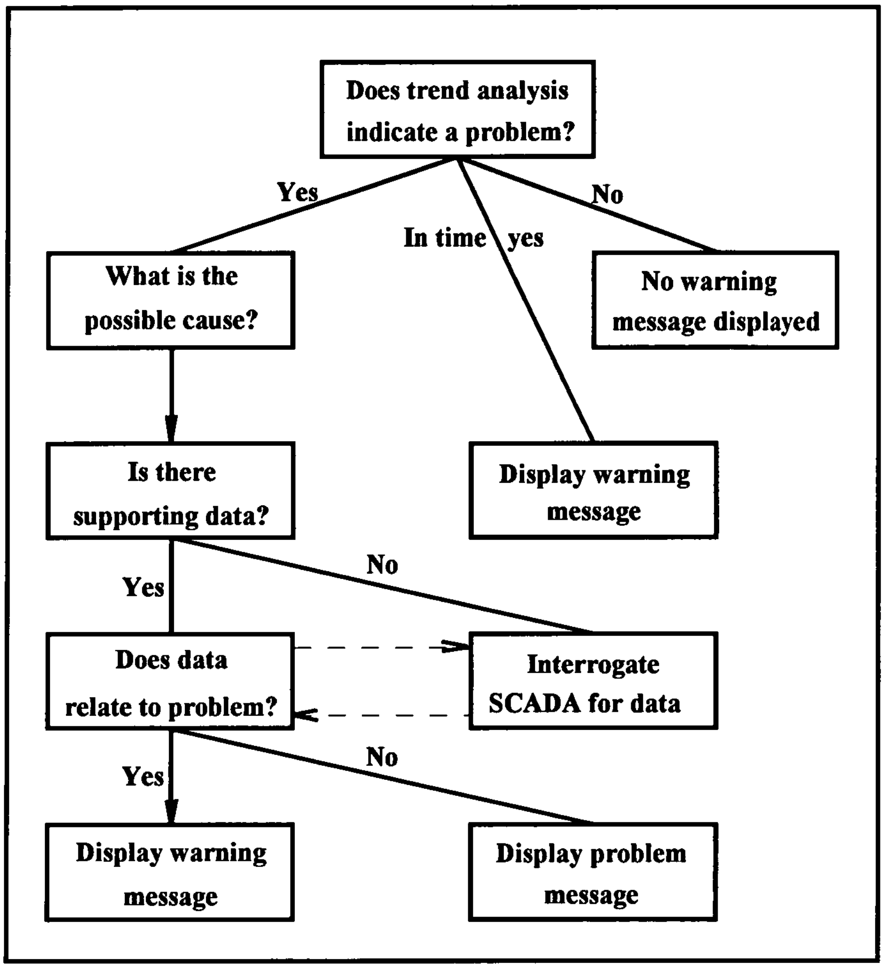


Figure 3.20: Problem Determination

4. SYSTEM DEVELOPMENT

4.1 General

Figure 4.1 displays the project outline in Gantt chart form. The project was started in April 1995. Generally, meetings of about an hour's duration were held with the project team every week. Initially, the process of manufacture of green anodes was discussed, with special reference to problems, and the detail scope of the project evolved. By August 1995, a basic application had been developed that ran on the plant network using live data, displaying a single trend chart and associated messages for each of four process variables associated with the forming of anodes. From this review point, the ensuing development work and discussions involved determining the knowledge base to cover the two critical areas of anode manufacture, namely, paste mixing and anode forming, and determining the way to present the information to the operator.

During the first six months of 1996, the most effective way of retrieving point values from SCADA was determined and the application extended to present data in a standard statistical process control format by way of three associated charts, Shewhart, CUSUM and EWMA charts, for nine process variables. A major effort was made to improve the robustness of the program which was prone to crashing in an apparent random manner. These problems were ascribed to deficiencies in the Level5 software and were to some extent minimised by working around them.

In the third quarter of 1996, the application was extended to include fines preparation. In the final quarter, the application was successfully tested on a new release of Level5 Object and ran for hundreds of trouble free hours. The new release had been developed to address the software problems previously experienced and was supplied free of charge for software testing. The application was further fine tuned and installed on-line for use by the process operators early in 1997.

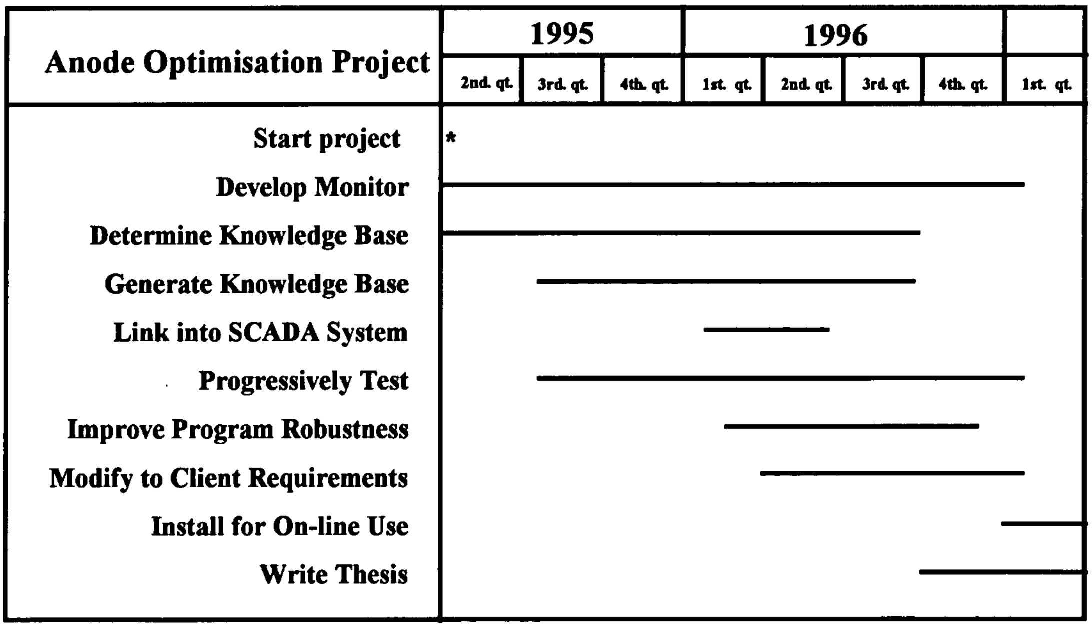


Figure 4.1: Project Outline

4.2 Software and Hardware

The software used was Level5 Object (L5O) supplied by Information Builders Inc. of the USA. Initially, started with release 3.5 and then successively upgraded to 3.6, to 3.6.2 by patches and finally to release 3.7 as software problems were identified and resolved by the suppliers. Communication regarding perceived software problems was originally with the distributors for Information Builders in Melbourne. However, since the client base in Australia was small and customer support in Melbourne referred most queries to the US, it was mutually agreed that further communication should be direct to the suppliers in Melbourne(!), Florida. This was done by fax and the arrangement worked successfully with reasonably prompt responses. On one occasion it was necessary to send a modified (to preserve some confidentiality) version of the application to illustrate the nature of the random failures.

The majority of the development work was carried out on a stand-alone PC off the plant. Initially started with a 386, then upgraded to a 486 with 8 Mb of RAM because the 386 was far too slow. In the last nine months of the project, the 486 was upgraded to 16 Mb of RAM and loaded with Windows NT. Testing on live data was carried out via a modem connecting into the plant's network.

4.3 Testing Procedures

Development has been predominantly carried out on realistic, but non-live data. This data was obtained by copying three hours of data from the relevant tables from the SCADA database in July 1995 into Access files *press_2.mdb* and *g_sieve.mdb.* These db files are listed in Appendix Tables 3.1 to 3.3 in Appendix 3.

A conversation is held between a Level5 application and an Access file utilising a Microsoft Open DataBase Connectivity (ODBC) interface. The links between the monitor and the SCADA and user databases are listed in Table 4.1. The appendage *_test* to a data source name indicates use of the non-live data for test and development purposes. During development and when running on live data, the data source name is readily changed in the L5O application.

Data source name	**Data source**	**db Tables**
anodedatg	SCADA: anodedatg	gc_anode, gc_batch
anodedatg_test	Access: press_2.mdb	gc_anode, gc_batch
accessp	SCADA: accessp	g_sieve
accessp_test	Access: g_sieve.mdb	g_sieve
pressdata	Access: pressdat.mdb	mess_text, anodelimit

Table 4.1: ODBC Links from Monitor to Data Sources

As the basis of this monitor is the analysis of populations of readings, the first step was to build routines to plot the readings, set points and trend line. To check the accuracy of these routines, the readings were also transferred to an Excel file for display of readings and trend line. Print-outs of the charts so obtained from the L5O routines and Excel were then compared. Consideration was given to using the capabilities of Excel directly, but discounted due to the complexity of generating and transferring the data to Excel to produce the three charts required for each process variable. From there, the rule base was built up and progressively tested in as rigorous manner as possible on the test data.

Every fortnight, to coincide with the running of the Green Carbon Plant, the application was run on a PC on the plant directly linked into the SCADA system over the plant's network. Thus, the application was tested against live data necessitating further modifications to the programming of the rule base. It also gave a chance for the other project team members to view the application and comment.

The structure of the program was changed several times in an endeavour to overcome problems and make it run more effectively and efficiently. By early 1996, a reasonable program structure had been developed dealing with nine process variables, though at this stage, only plotting a single chart showing readings, set points and a trend line. In test mode, the application would cycle through a complete analysis in three minutes.

It became apparent that the application was subject to random failure after only a few cycles, ie the application would stop running and require re-starting. On occasion, it would crash and the PC require re-booting. The problem was to identify whether the failures were truly random and if not, where the failures were occurring. When installed for on-line use by the operators, the monitor would need to run continuously without failure for a complete production run of ten days, ie 1500 cycles.

A separate routine of similar structure was used for the analysis of each of the nine process variables. Ten error markers were placed between the same lines of code in each of the routines. Thus, routine 1 would have error markers 10 to 19, routine 2 would have error markers 20 to 29 and so on. As the program ran, the current error marker and cycle counter would be displayed on the screen. The application was run to failure, the error marker number, cycle counter and error message noted and the application re-started. Gradually a pattern emerged. Some of these failures were due to faulty programming and were remedied. Generally, the failures were occurring in a few places in some, but not all, of the routines. The randomness was related to the number of cycles to failure, usually less than ten. As the failures were occurring at only a few places, more error markers were added till the "faulty" line of code was isolated. That line of code was then re-worked. In this way, reliability was improved to a mean time between failures of more than 100 cycles which fell a long way short of the target of 1500 cycles. This aspect of testing proved to be extremely time consuming and frustrating. However, in the process of trying to eliminate perceived problems much was learnt about the structuring and debugging of programs.

Between May and October, the rule base was extended and the number of graphs on each display increased to three. With each change, reliability plummeted to less than ten cycles between failures. There were also other indications of memory loss that did not cause the program to stop running, such as loss of a line on a chart, or loss of data in a table. This inability to work around this problem cast considerable doubt on the viability of using Level5 Object in a production environment.

Information Builders were not very helpful on this reliability aspect, ascribing the problem to faulty programming but suggesting that they test the application. To that end, a simple version of the application dealing with the charting only, but without the rule base, was sent to them for testing in May 1996. In August, they replied that they had duplicated the problems experienced and that the cause was due to memory leakage in the software memory management. In October, they sent a new version for pre-release testing that addressed this memory leakage problem.

In mid-1996, the PC was upgraded and a modem installed. This permitted testing on live data from off the plant, though only during the weekends. During the week, even after hours, the network was so busy that access by modem to SCADA was rarely possible. As running on live data exposed the application to process conditions not covered during the earlier stages of development, the need for further modifications was identified. In this period, a routine was added to cover fines preparation.

The new version of L5O was received in October and run continuously as much as possible. In three months it ran 14000 cycles intermittently, sometimes on test data and sometimes on live data via the modem connected to the plant, with only two failures, when it lost graphic support and crashed. This was ascribed by Information Builders to lack of memory in the PC, not software memory leakage. Despite pruning out all files not required, there was only about 10 Mb of memory spare and NT is rather greedy in its use of memory. Several times a "Running out of memory" message was displayed.

4.4 Problems Experienced

Some of the problems with hardware have already been alluded to in that the PC required upgrading twice to match the demands of the monitor's development. L5O is heavy on memory to start with. Added to that, Microsoft Assess and Excel are very demanding on RAM memory and NT uses about 30 Mb of memory as a buffer. L5O could not be loaded directly into NT on four separate PC's on the plant but had to be loaded via Workgroups for Windows despite assurances from Information Builders that it was compatible with NT. However, problems had been experienced with loading other software packages into NT on the plant, so the problem may not lie with L5O but with an incompatibility with files common to the plant such as those related to the network. The application runs well on a Pentium in Windows NT in the control room. However, the operators use the PC for other applications such as preparing reports and the like, whilst the monitor is running. This concurrent running of several different applications caused the monitor to crash on occasion. It is most probable that the process monitor, as presently conceived, will have to run on a dedicated PC in the production environment.

Most of the problems with the software have been dealt with. It only remains to be said that Information Builders successfully solved the memory leakage problems. One known shortcoming of L5O is the inability to customise a chart, especially in relation to data labelling and their spacing on the axes (refer to Figure 4.2). Information Builders advise that this issue will be addressed in release 4.0.

A further problem, if it can be described a problem, is that the scope of the project started off as rather tenuous. The scope evolved during the project's development as the various parties sorted out their ideas and learnt what was possible when using an expert system. By the end of 1995, the scope of the knowledge base was reasonably established though the rule base for fines preparation was changed late in 1996 in response to a change in the operating criteria resulting from feed-back in running the process monitor. The method of the presentation of statistical process control information was finalised by mid-1996 from a single chart showing trends to the display of three charts. This evolvement of the project's scope has led to a decision support system that properly meets the user's requirements.

4.5 Running the Monitor

The application is started by clicking on an icon. This opens up the L5O *monitor.knb* file, opens up the links with SCADA and opens the Access and Excel files. A blank screen is displayed with the first button labelled *"Click" to Start*. Figures 4.2 to 4.12 shows screen dumps of one cycle of displays that an operator sees.

On starting the application, the role of the first push-button changes to indicate the program phase. It progressively shows *Accessing NIF*, then *Accessing db* and *Charting* as the application works through to the first program routine. After about a minute the first screen is displayed, headed *Anode Weight*, which shows three statistical process control graphs and a message table for Anode Weight. The first button shows *User Control*. If the *Hold* button is clicked by the user, the display will be held until the *Continue* button is clicked or 5 minutes elapses, else the application proceeds to the next routine after 30 seconds. If the *Hold* button is clicked, the user can study the screen, do a screen dump by clicking on the *Print* button or view an SOP by clicking on the hypertext *Click for SOP*. The *Exit* button allows the user to stop the run, wherein the data links and files are properly closed and the initial start screen displayed. The number shown in the message table heading is the number of readings sampled. None of the buttons can be activated unless the first button shows *User Control*. The *Continue* and *Print* buttons cannot be activated unless the *Hold* button has been clicked and is highlighted.

The process variables dealt with are Anode Weight, Anode Height, Hopper Weight, Pitch Level, Green Apparent Density, Anode minus Hopper Weight, Press Pressure, P2 Temperature, Press Paste Temperature, Ball Mill Operation and Status Summary.

If the *Hold* button is not clicked during a cycle, the process monitor takes ten minutes to cycle through all the analysis routines, after which it repeats the cycle by accessing SCADA again to retrieve data. It continues to cycle through the routines until shut down by the user. In the event that production ceases or data links are broken, it bypasses the analysis routines and displays the appropriate message in the Status Summary Table, cycling every five minutes until anode production resumes or the data links are restored.

4.6 Project Sponsor's Review

The sponsor's review of this project is presented in Appendix 6.

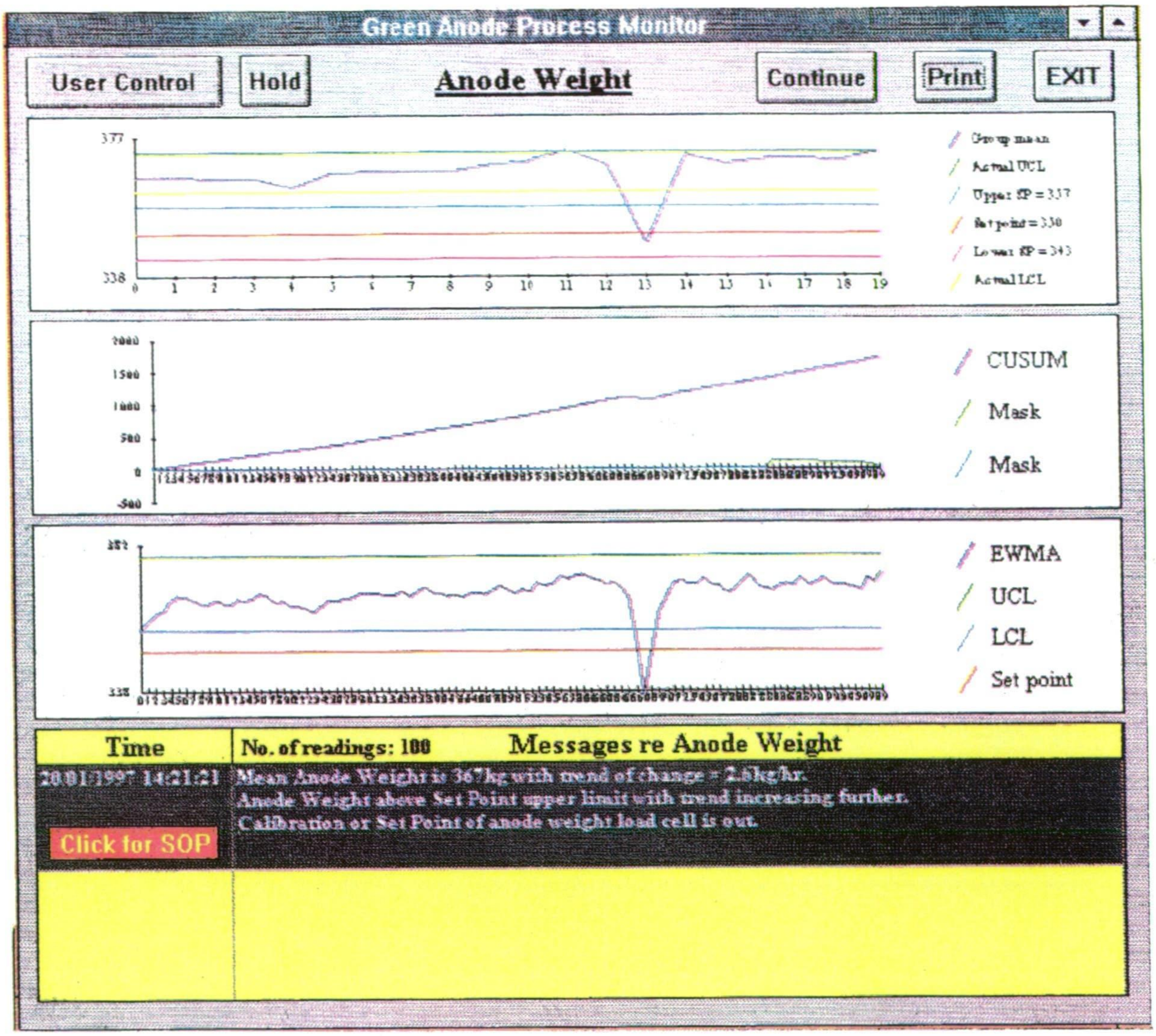


Figure 4.2: Display of Process Control Data for Anode Weight

This figure shows that the process of regulating the anode weight is out of control. In the CUSUM chart, the tail of the CUSUM line is so far away from the mask that the mask can barely be seen. This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart being above the upper set point. In the Message Table, the mean anode weight is given as 367kg against a set point of 350kg and above the upper set point of 357kg. The cause of the problem is given as the calibration or set point of the anode weight being out. The background colour of the table is black and yellow indicating that there is a problem. The hypertext 'Click for SOP' is displayed.

Note that on the Shewhart chart is a plot of the mean of successive groups of five readings. Note also the inability to customise the labelling on the axes, especially on the x-axis.

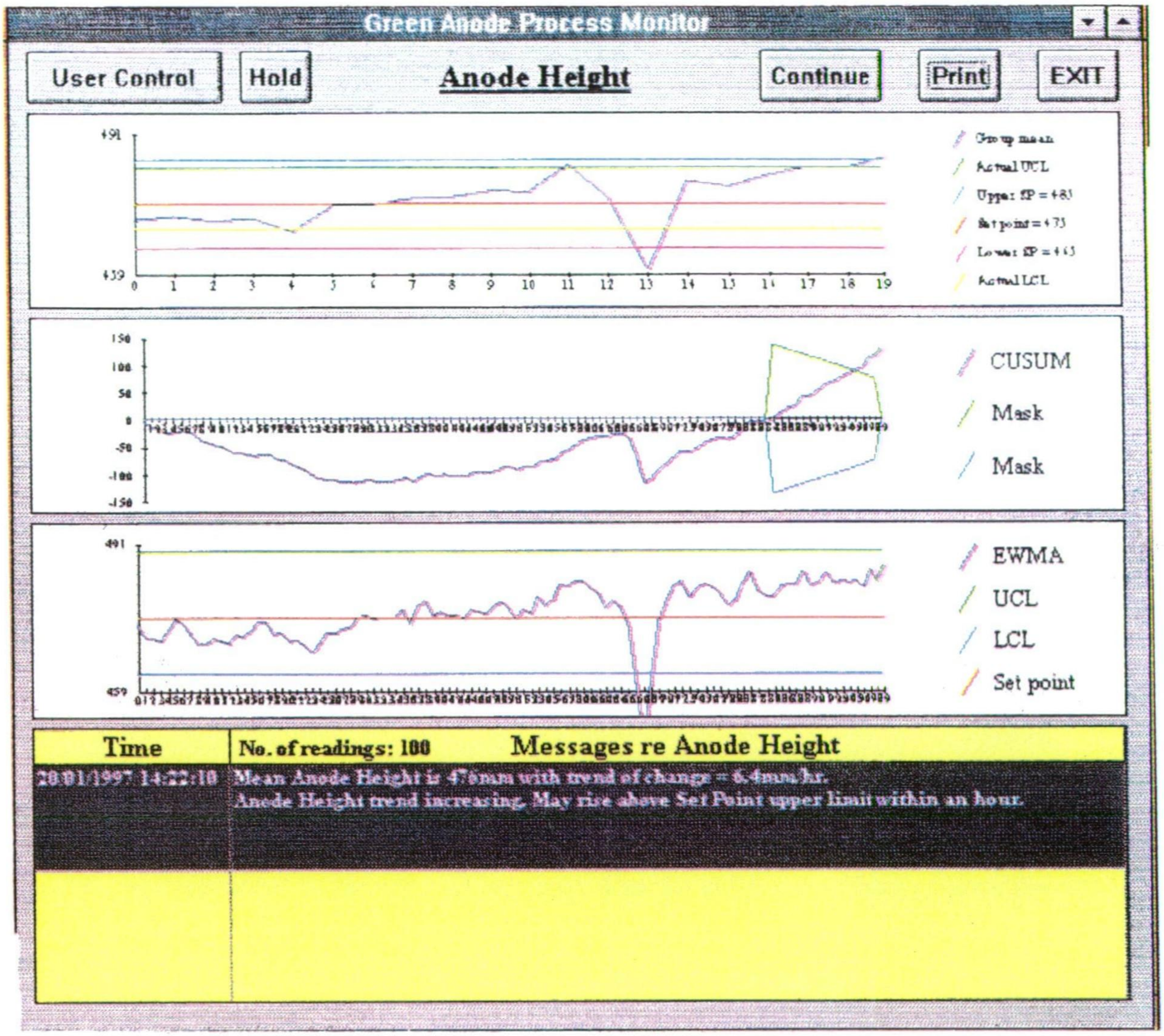


Figure 4.3: Display of Process Control Data for Anode Height

This figure shows that the process of regulating the anode height is going out of control. In the CUSUM chart, the tail of the CUSUM line is passing through the mask. This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart trending upwards. In the Message Table, the mean anode height is given as 476mm against a set point of 475mm with a trend of 6.4mm/hr and a warning that the mean may rise above the upper set point within an hour. The background colour of the table is black and yellow indicating that there is a problem or potential problem. The hypertext 'Click for SOP' is not displayed as, in this instance, there is only a potential problem.

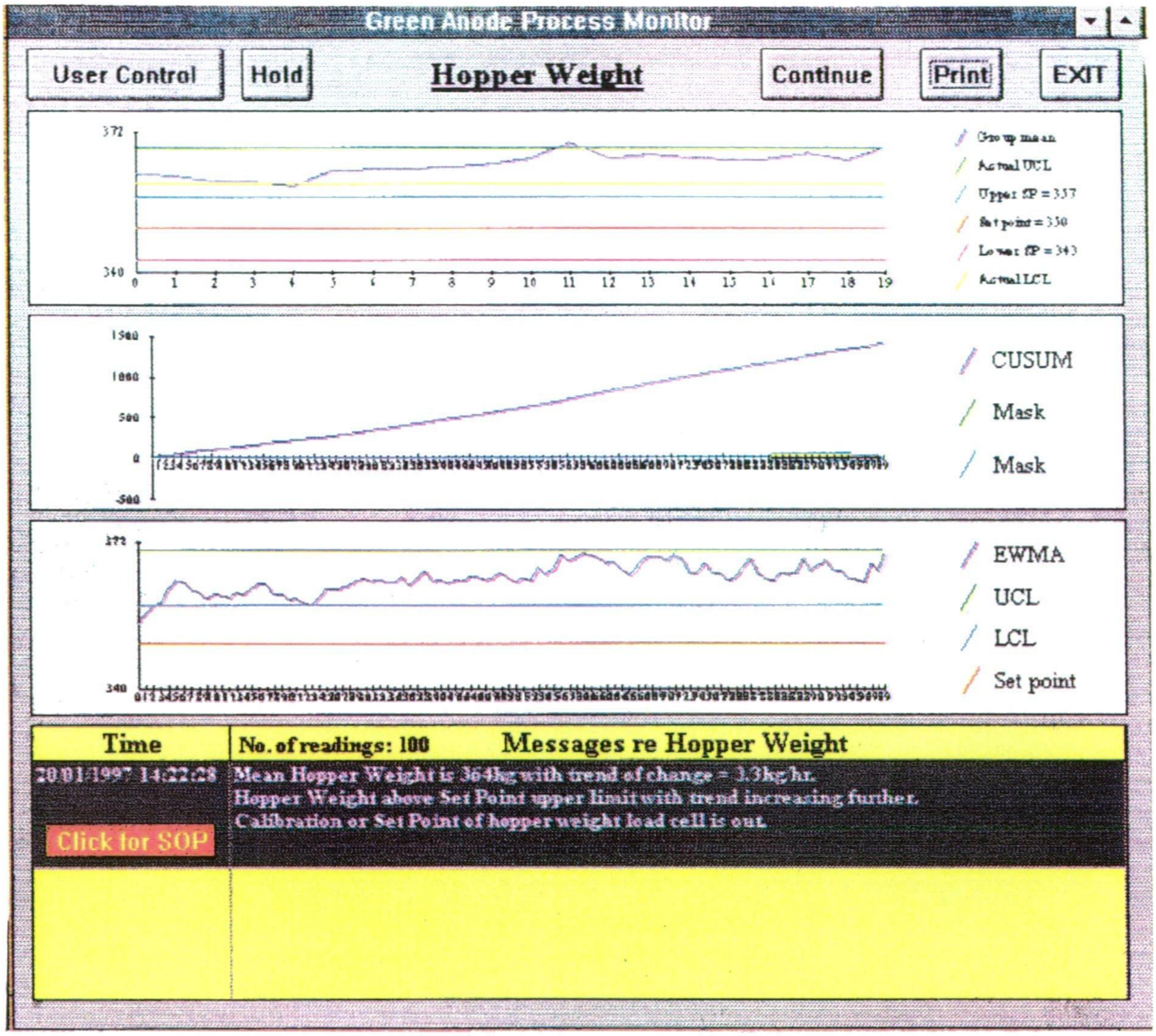


Figure 4.4: Display of Process Control Data for Hopper Weight

This figure shows that the process of regulating the hopper weight is out of control. In the CUSUM chart, the tail of the CUSUM line is so far away from the mask that the mask can barely be seen. This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart being above the upper set point. In the Message Table, the mean hopper weight is given as 364kg against a set point of 350kg and above the upper set point of 357kg. The cause of the problem is given as the calibration or set point of the hopper weight load cell being out. The background colour of the table is black and yellow indicating that there is a problem and the hypertext 'Click for SOP' is also displayed.

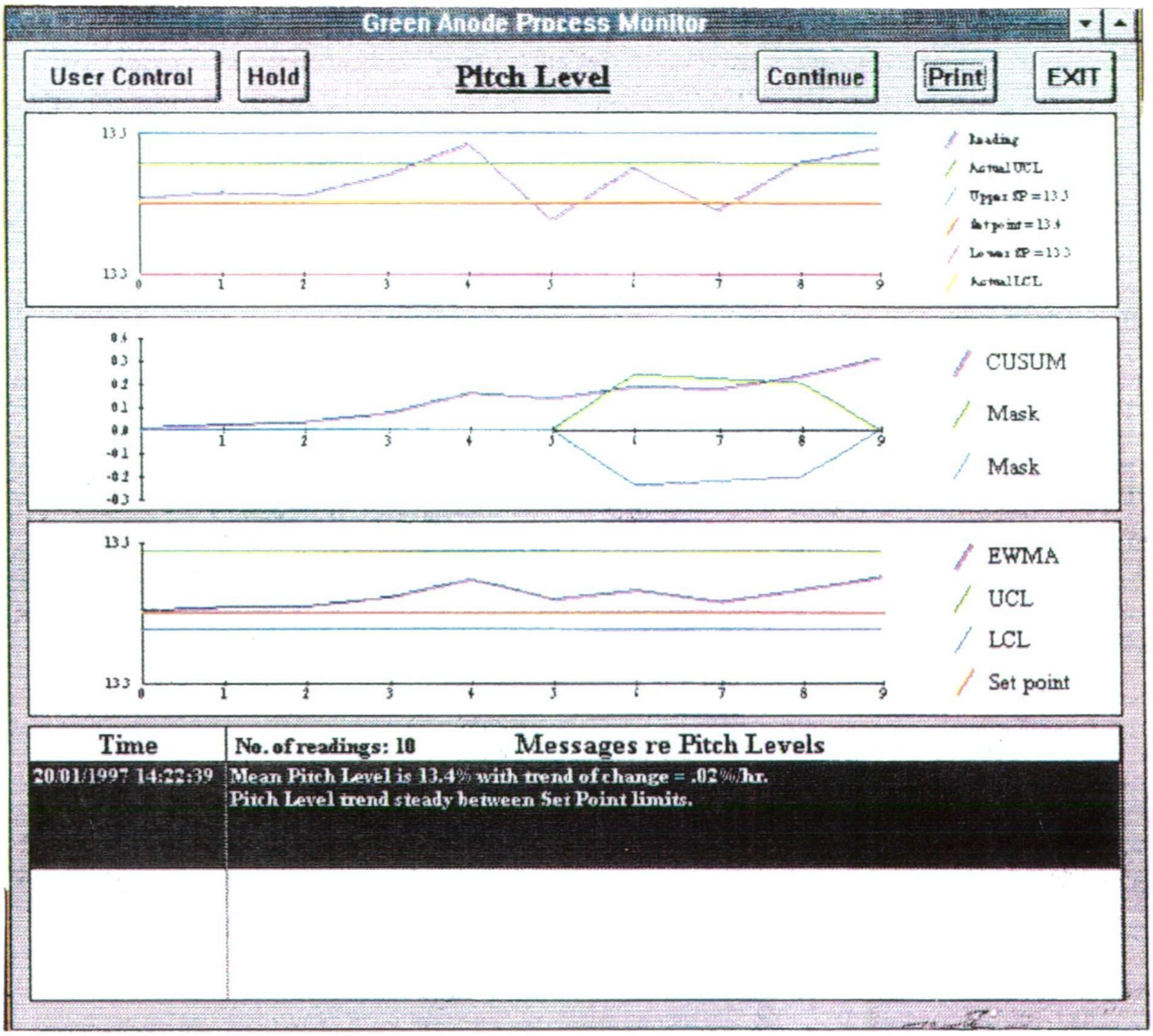


Figure 4.5: Display of Process Control Data for Pitch Levels

This figure shows that the process of regulating the pitch level is in control. In the CUSUM chart, the tail of the CUSUM line is within the mask (the line at the left hand end of the mask should be vertical, but due to the limitations of the graphics and paucity of data, this line is inclined at 40°). This is confirmed by the group mean line on the first (Shewhart) chart being contained between the upper and lower set points. In the Message Table, the mean pitch level is given as 13.4% against a set point of 13.4% with trend steady between the set points. The background colour of the table is black and white indicating that there is no problem.

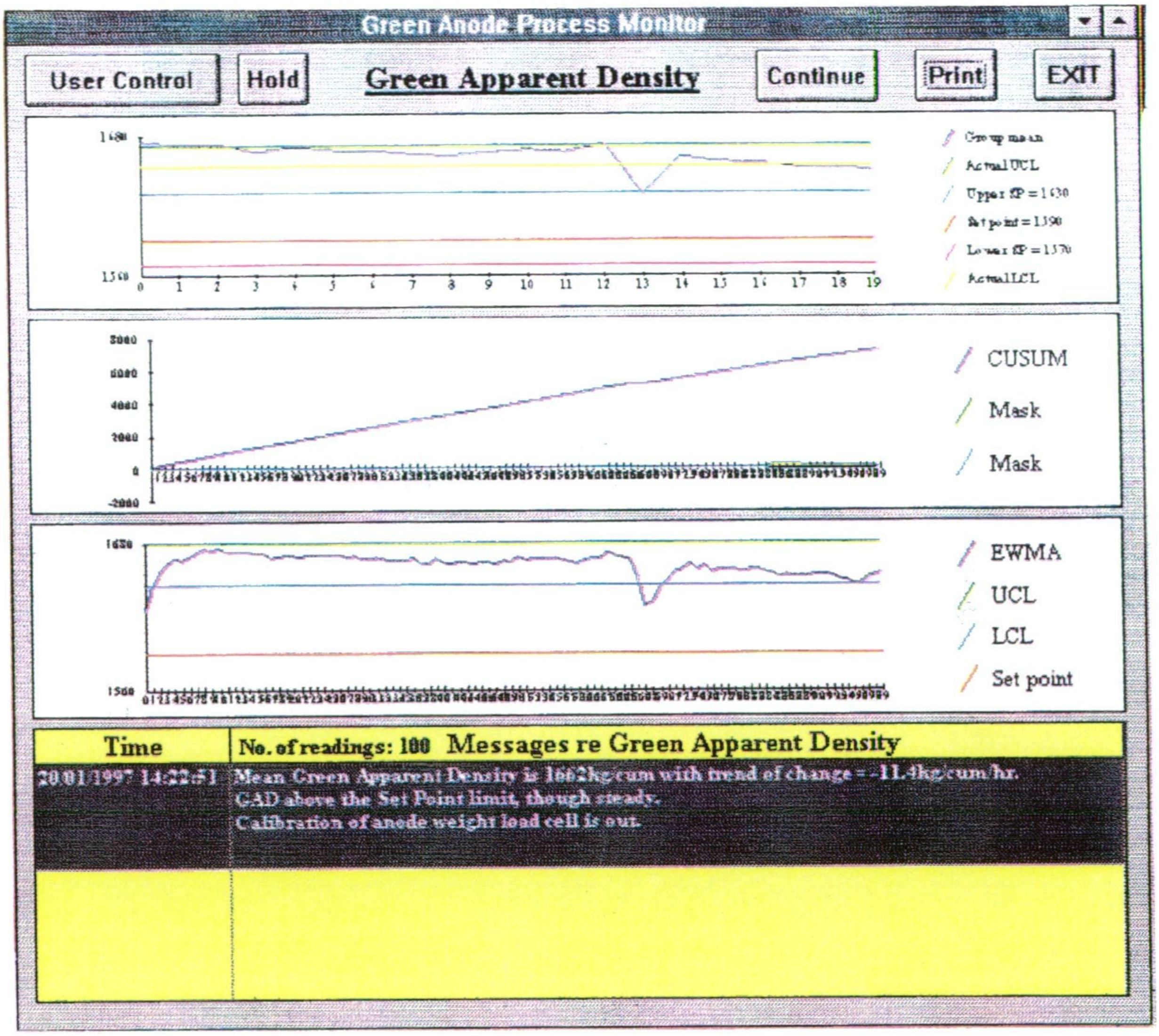


Figure 4.6: Display of Process Control Data for Green Apparent Density

This figure shows that the process of regulating the green apparent density is out of control. In the CUSUM chart, the tail of the CUSUM line is so far away from the mask that the mask can barely be seen. This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart being above the upper set point. In the Message Table, the mean GAD is given as 1662kg/m^3 against a set point of 1590 kg/m^3 and above the upper set point of 1630 kg/m^3. The cause of the problem is given as the calibration or set point of the anode weight load cell being out. The background colour of the table is black and yellow indicating that there is a problem.

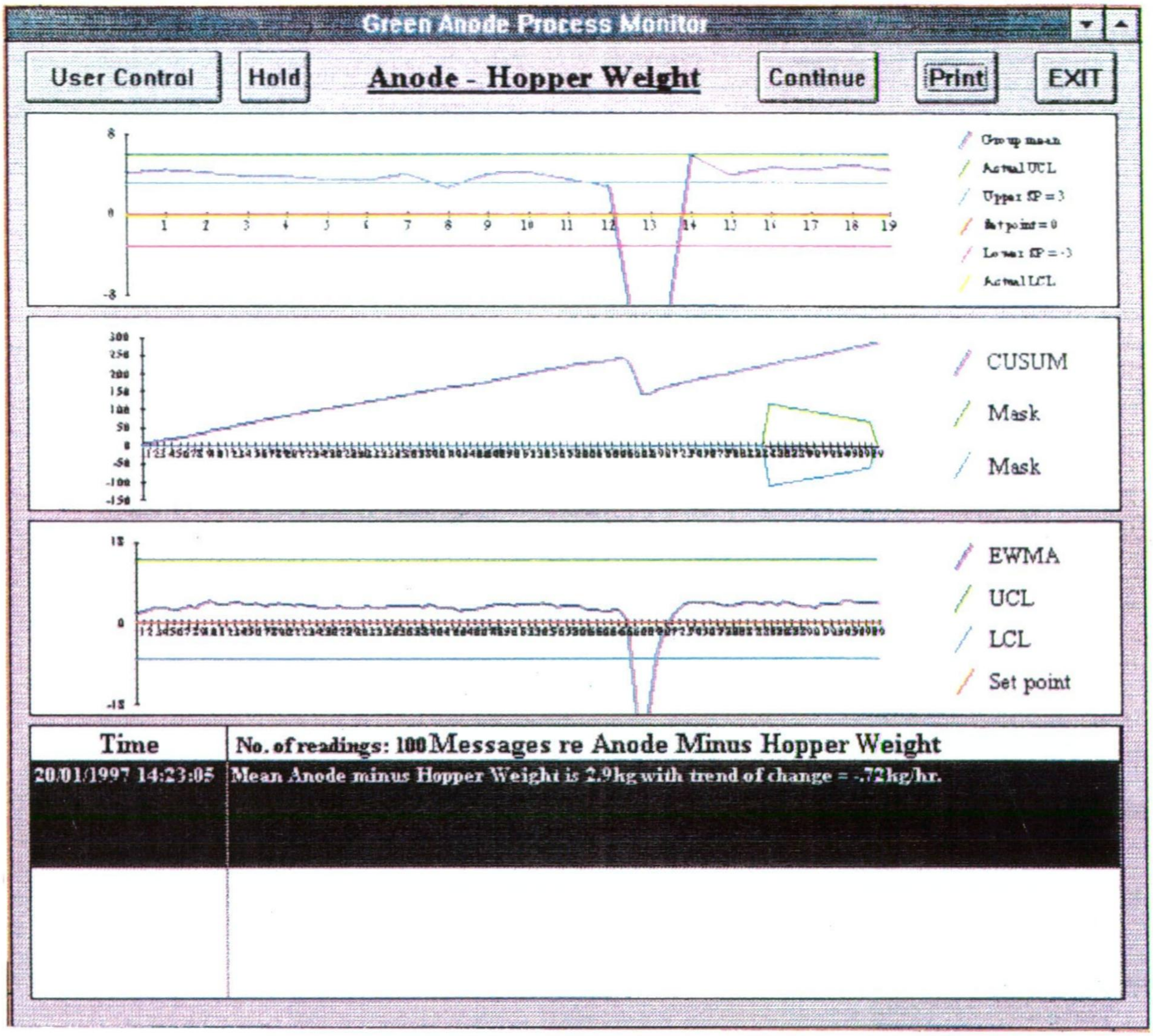


Figure 4.7: Display of Process Control Data for Anode Minus Hopper Weight

This figure shows that the process of regulating the anode or hopper weight is out of control. In the CUSUM chart, the tail of the CUSUM line is away from the mask. However, the difference between the two weights is within 3kg of the set point. This is confirmed in the Message Table, where the mean anode minus hopper weight is given as 2.9kg. The background colour of the table is black and white indicating that there is not a problem in this context though previous displays have indicated otherwise.

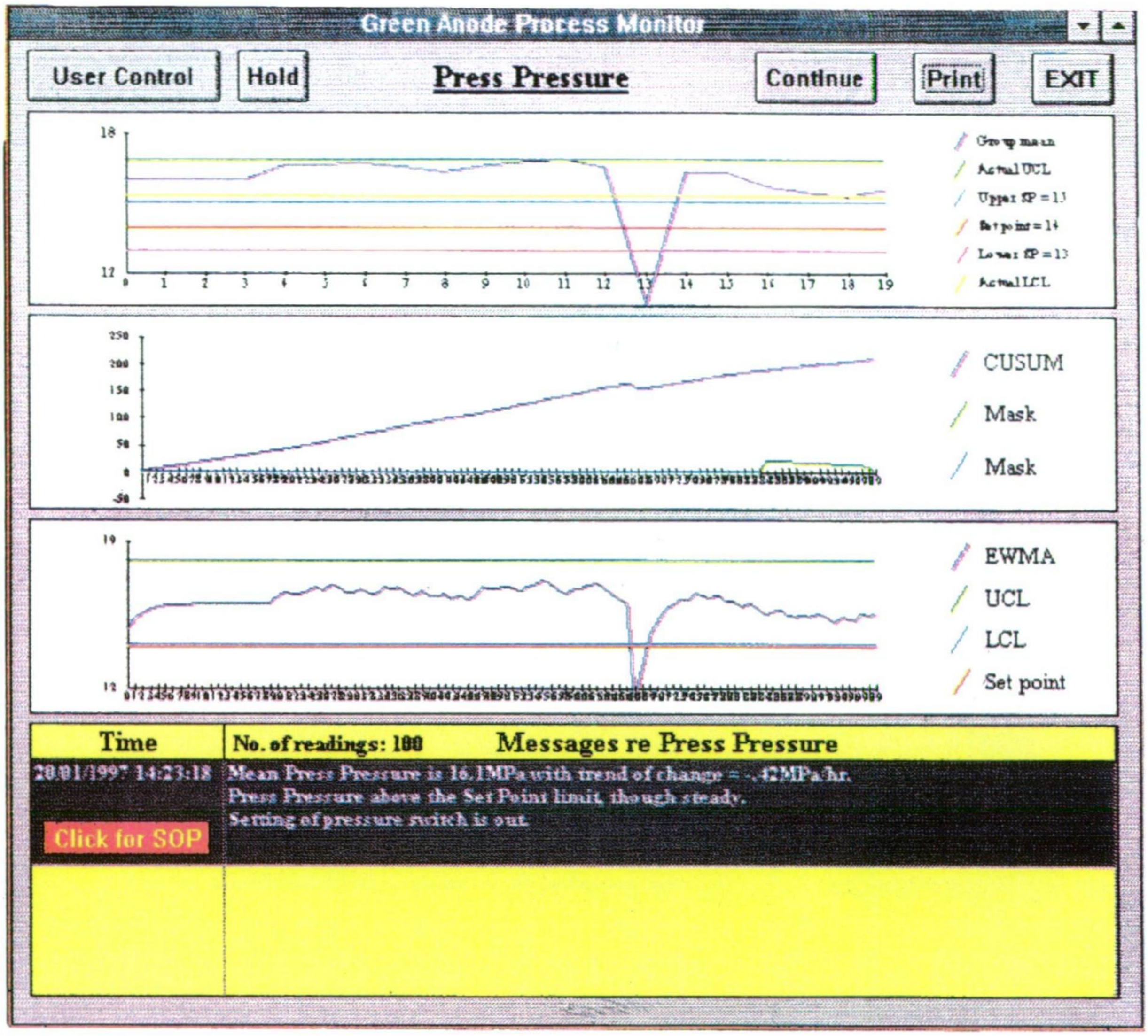


Figure 4.8: Display of Process Control Data for Press Pressure

This figure shows that the process of regulating the press pressure is out of control. In the CUSUM chart, the tail of the CUSUM line is so far away from the mask that the mask can barely be seen. This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart being above the upper set point. In the Message Table, the mean press pressure is given as 16.1MPa against a set point of 14MPa and above the upper set point of 15MPa. The cause of the problem is given as the setting of the pressure switch being out. The background colour of the table is black and yellow indicating that there is a problem and the hypertext ‘Click for SOP’ is also displayed.

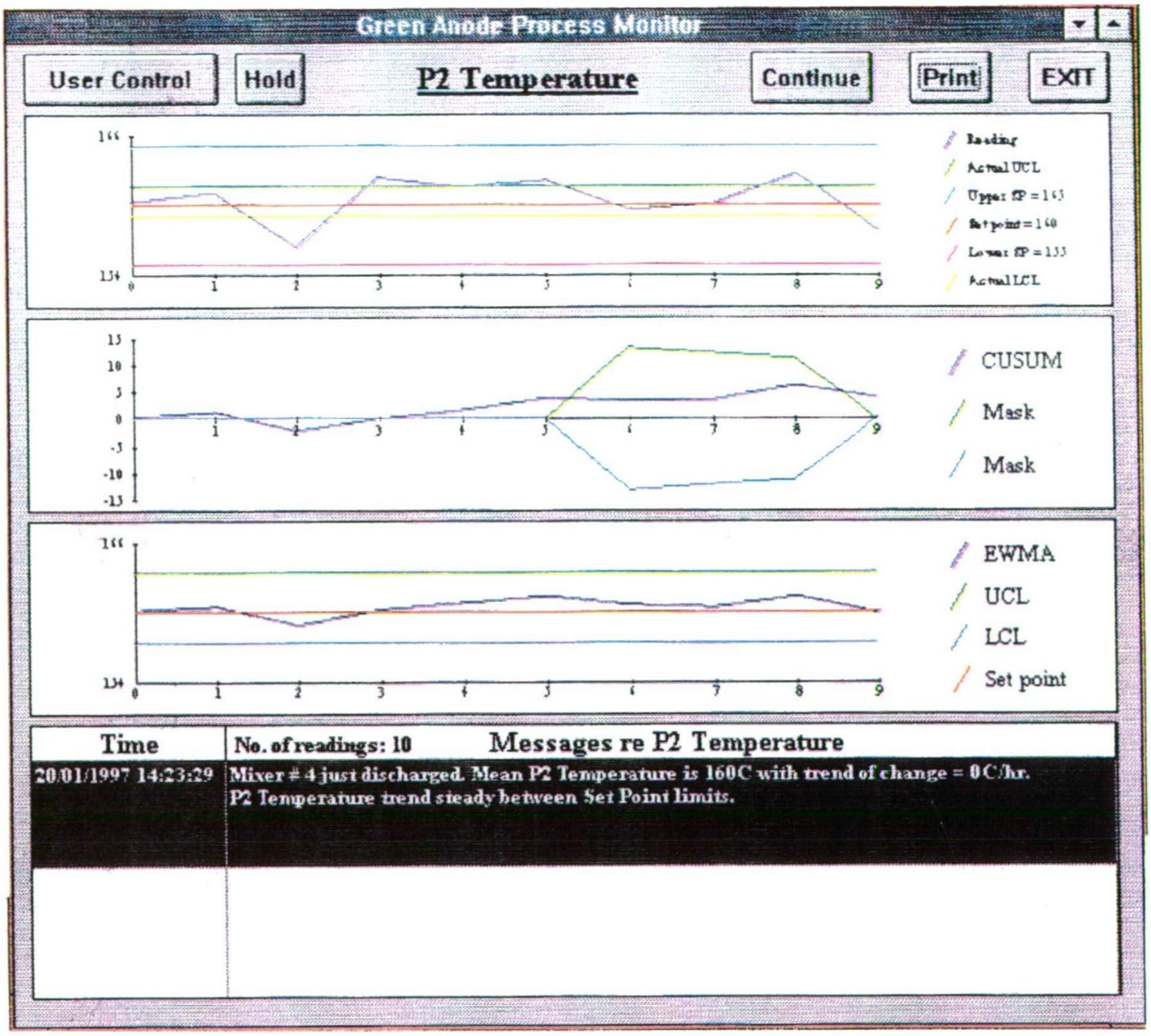


Figure 4.9: Display of Process Control Data for P2 Temperature

This figure shows that the process of regulating P2 temperature is in control. In the CUSUM chart, the tail of the CUSUM line is contained within the mask This is confirmed by the group mean line on the first (Shewhart) chart and the EWMA line on the third chart being contained between the upper and lower set points. The mean P2 temperature is given as 160°C against a set point of 160°C with trend steady.

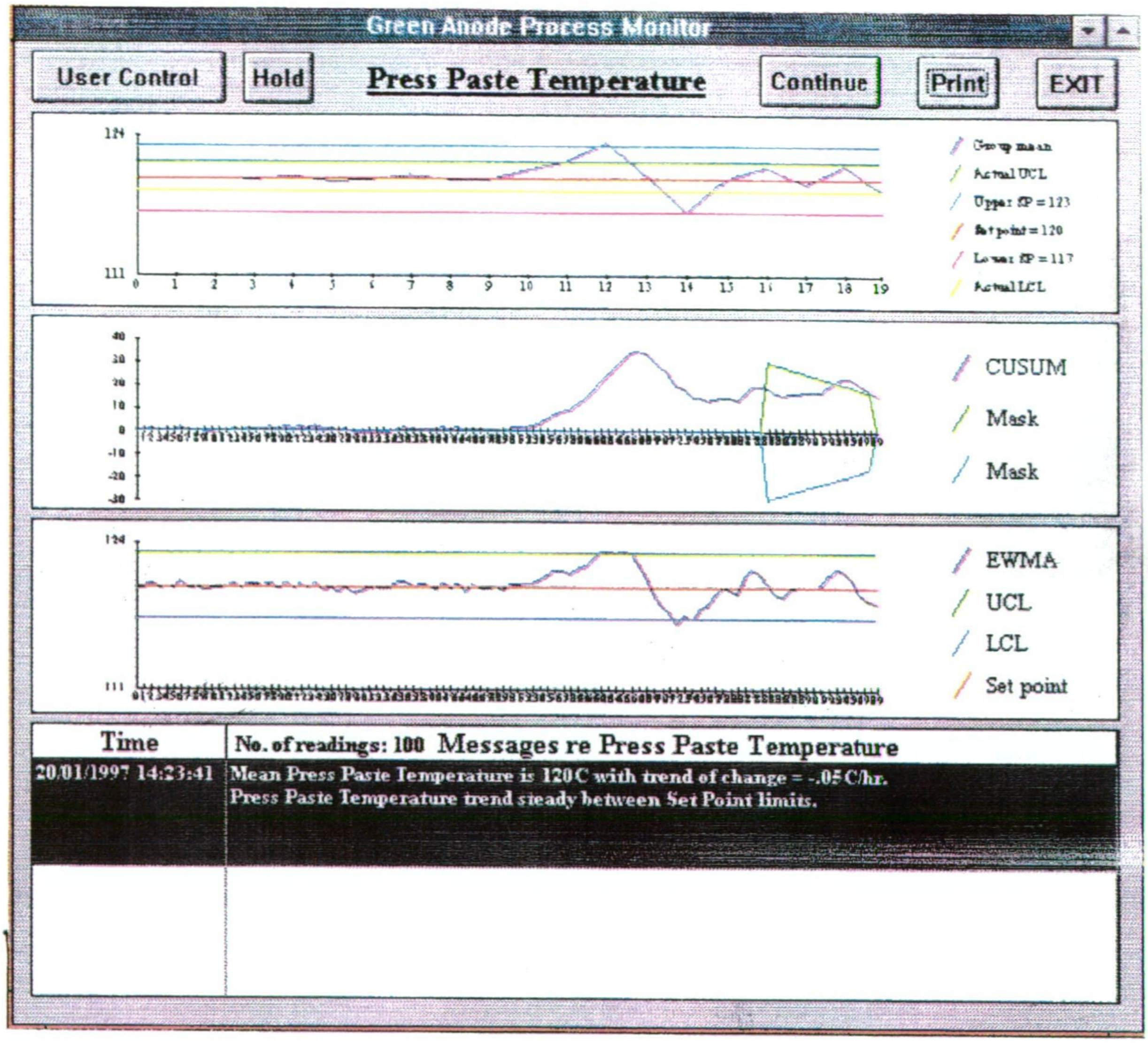


Figure 4.10: Display of Process Control Data for Press Paste Temperature

This figure shows that the process of regulating the press paste temperature is not totally in control as the tail of the CUSUM line is out of the mask and there is more scatter on the other two charts. However, mean press paste temperature is 121°C and steady between set point limits of 117°C and 123°C. Generally, control has been held tightly within a band of width of 2°C, as indicated by the upper and lower control limits.

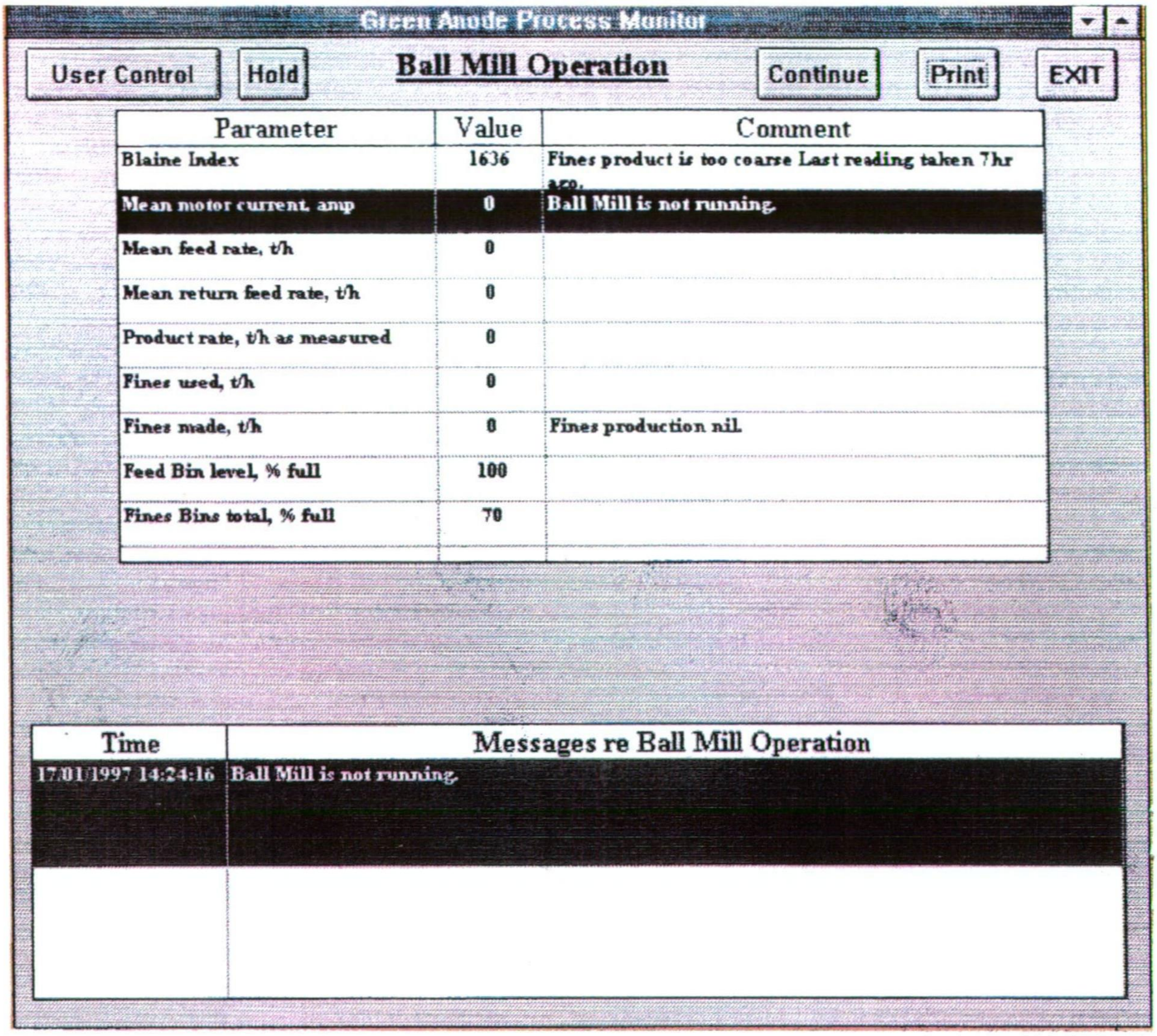


Figure 4.11: Display of Process Control Data for Ball Mill Operation

This shows that the Ball Mill is not running, the feed bin (feeding the Ball Mill) is full and the fines bins (feeding the mixers) is 70% full. It also shows that the Blaine Index is low at 1636, indicating a coarse product and was taken seven hours ago. This measurement should be taken every four hours.

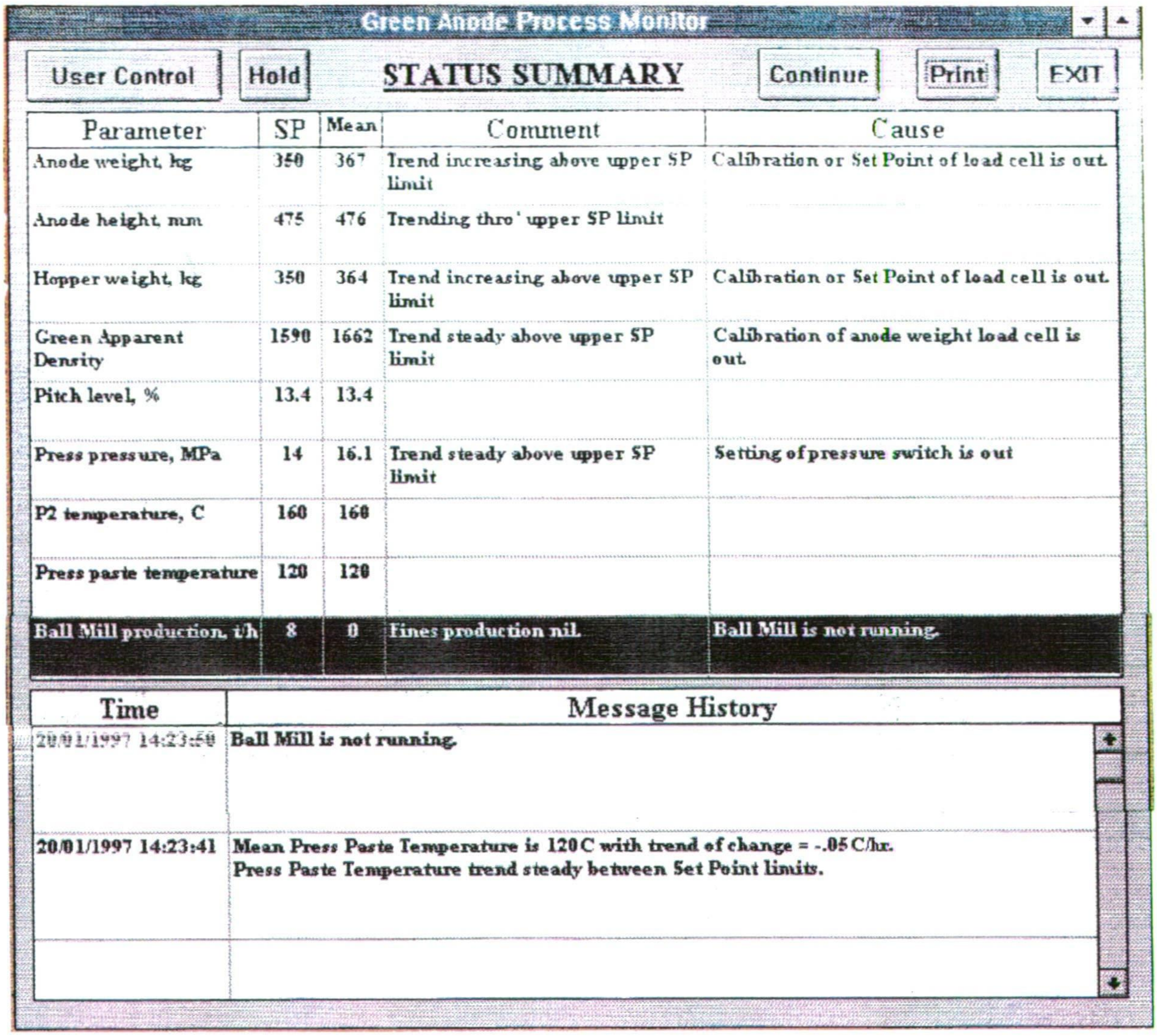


Figure 4.12: Display of Process Control Data for Status Summary Screen

This screen provides a status summary of the nine process variables, showing the mean against the set point, a comment regarding a problem and the cause of said problem. If there is not a problem, then the field is left blank. Below the Status Summary table, is a Message History table. If the 'Hold' button is clicked, the table can be scrolled through to view all the messages in the past two hours starting with the most recent.

5. CONCLUSION

A decision support system, based on an expert system, has been developed to continuously monitor the complex process of anode production at an aluminium smelter. The monitor interacts with the SCADA process control system in real-time, extracting data from the database and ascertaining point values. It applies rules from the knowledge base in order to determine whether the process is in control, about to go out of control or out of control. For each of ten process variables, it displays a triplet of statistical process control charts and messages advising of trends, potential problems and possible causes of those problems. Utilising hypertext, the operator can view and print out a Standard Operating Procedure that describes how to rectify said problem.

The research has established the necessary techniques to design a system to continuously oversee and monitor a complex production process, to analyse large amounts of data in real time and provide meaningful and timely information to the operator to enable the operator to take any necessary corrective action required.

The provision of this process monitor enables an operator to control the process within tighter limits, optimising the production process in order to obtain anodes of a consistent and high quality.

Until close to the completion of this project, serious doubts were held as to the ability of an application to run continuously utilising the *Level5 Object* software package without falling over. However, the cause of the problem was identified and remedied by the developers, Information Builders Inc, in Release 3.7 of their *Level5 Object* software. Subsequent endurance testing now indicates that the developed process monitor should run without failure for the duration of a ten day production run on a dedicated PC.

It is anticipated that the techniques established by this research will be used as the basis for monitoring other production processes within the aluminium industry.

9. REFERENCES

Comalco Aluminium (Bell Bay) Ltd. (1996) *Introductory Statistical Process Control Course Outline.*

Feigenbaum E.A. & McCorduck P. (1981) *The Fifth Generation,* (Reading MA: Addison-Wesley Publishing)

Frenzel Jr. L.E. (1987) *Crash Course in Artificial Intelligence and Expert Systems,* (Indianapolis: Macmillan Inc.)

Goldberg D.E. (1989) *Genetic Algorithms in Search, Optimization and Machine Learning,* (Reading MA: Addison-Wesley Publishing)

Hayes-Roth F. (1992) *Expert Systems.* In Shipro S.C. (Ed.) *Encyclopedia of Artificial Intelligence, 2nd. Edition,* (New York: John Wiley)

Haykin S. (1994) *Neural Networks,* (New Jersey: Macmillan College Publishing Co.)

Holland J.H. (1962) *Concerning Efficient Adaptive Systems.* In Yovits M.C., Jacobi G.T. & Goldstein G.D. (Eds), *Self-organising Systems* pp 215-230 (Washington: Spartan Books)

Holland J.H. (1962) *Information Processing in Adaptive Systems.* Information Processing in the Nervous System, Proceedings of the International Union of Physiological Sciences, 3, pp 330-339.

Holland J.H. (1962) *Outline for the logical theory of Adaptive Systems.* Journal of the Association for Computing Machinery, 3, pp 297-314.

Kosko B. (1994) *Fuzzy Thinking,* (Glasgow: Harper Collins Manufacturing)

Lindsay R.K., Buchanan B.G., Feigenbaum E.A. and Lederberg J. (1980) *Application of Artificial Intellegence for Organic Chemistry: The DENDRAL Project* (New York: McGraw-Hill)

Meier M.W. (1996) *Cracking Behaviour of Anodes.* R & D Carbon (Sierre: Calligraphy)

Memmi D. (1989) *Connectionism and Artificial Intelligence* Neuro-Nimes 1989 International Workshop on Neural Networks and their Application, Nimes France.

Minski M.L. (1961) *Steps Towards Artificial Intelligence,* Proceedings of the Institute of Radio Engineers 49, pp 8-30.

Myers D.R. Davis J.F. and Hurley II C.H. (1990) *An Expert System for Diagnosis of a Sequential, PLC-Controlled Operation.* In Mavrovouniotis M.L. (Ed.), *Artificial Intelligence in Process Engineering*, (San Diego: Academic Press)

Okuda K. and Miyasaka N. {1990) *Model Based Intelligent Process Monitoring and Diagnosis - An Application to a Co-generation Plant.* Pacific Rim International Conference on Artificial Intelligence '90, pp 134-138.

Partridge D. (1990) *A New Guide to Artificial Intelligence*, (New Jersey: Ablex)

Payne E.C. and McArthur R.C. (1990) *Developing Expert Systems*, (New York: John Wiley & Sons.)

Pham D.T.(1988) *Expert Systems in Engineering.* In Taunton J.C. & Haspel D.W. (Eds) *The Application of Expert System Techniques in On-Line Process Control* (Bedford, UK: IFS Publications)

Pople H.E., Myers J.D. and Miller R.A. (1975) *"DIALOG INTERNIST: A Model of Diagnostic Logic for Internal Medicine* Proceedings of the Fourth IJCAI Tbilisi USSR, (San Mateo, Calif: Morgan Kaufmann)

Quinlan J.R. (1987) (Ed.), *Applications of Expert Systems*, (Reading MA: Addison-Wesley Publishing)

Rich E. (1983) *Artificial Intelligence*, (New York: McGraw Hill)

Schlimmer J.C. & Langley P. (1992) *Machine Learning.* In Shipro S.C. (Ed.) *Encyclopedia of Artificial Intelligence, 2nd. Edition*, (New York: John Wiley)

Shortliffe E.H. (1976) *Computer-Based Medical Consultation: MYCIN*, (New York: Elsevier Science Publishing Co.)

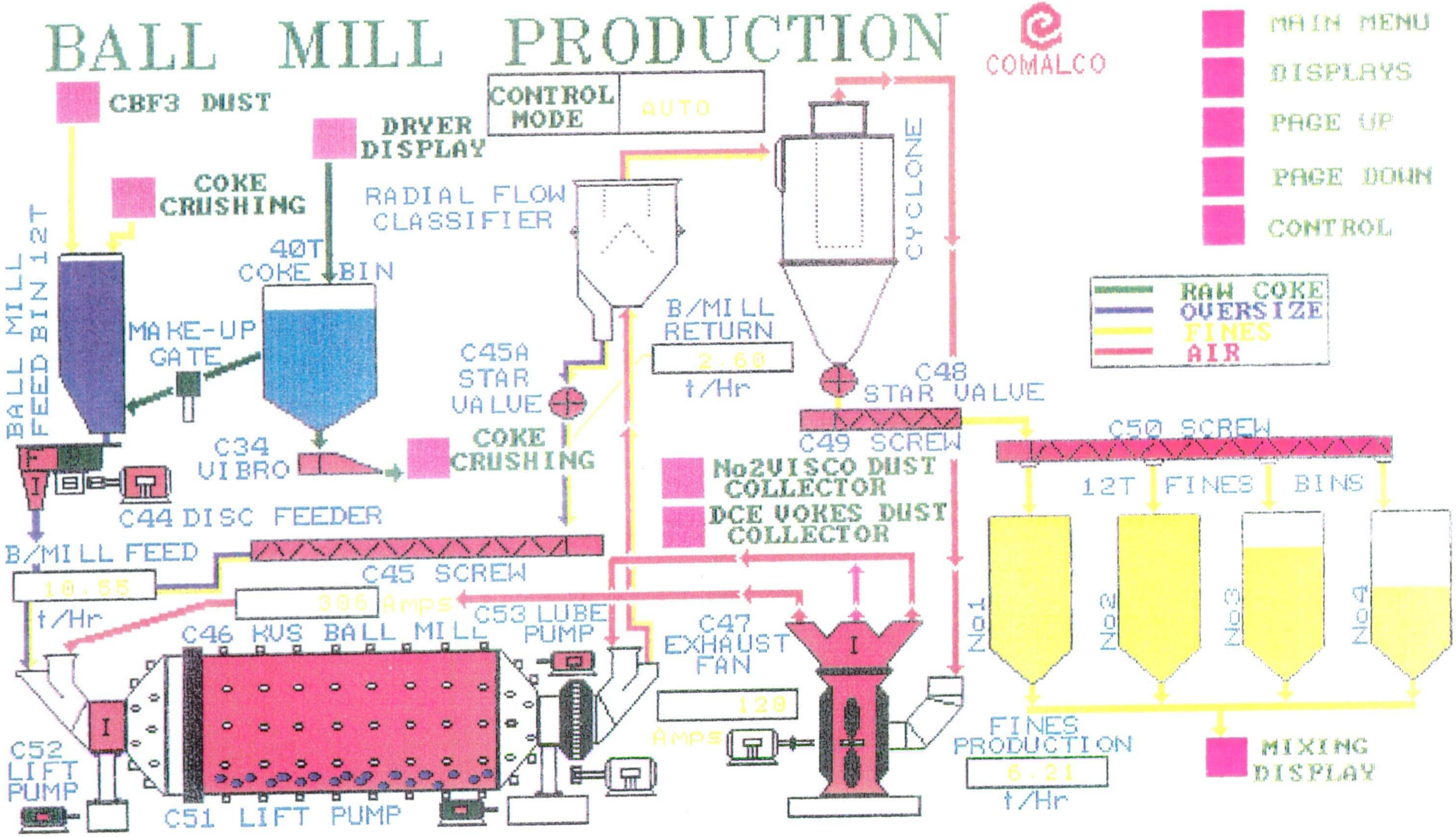
Sowerbutts J.W. (1993) *The Causes and Level of Variation in the Properties of Bell Bay Anodes*, Comalco Technical Report 93/217

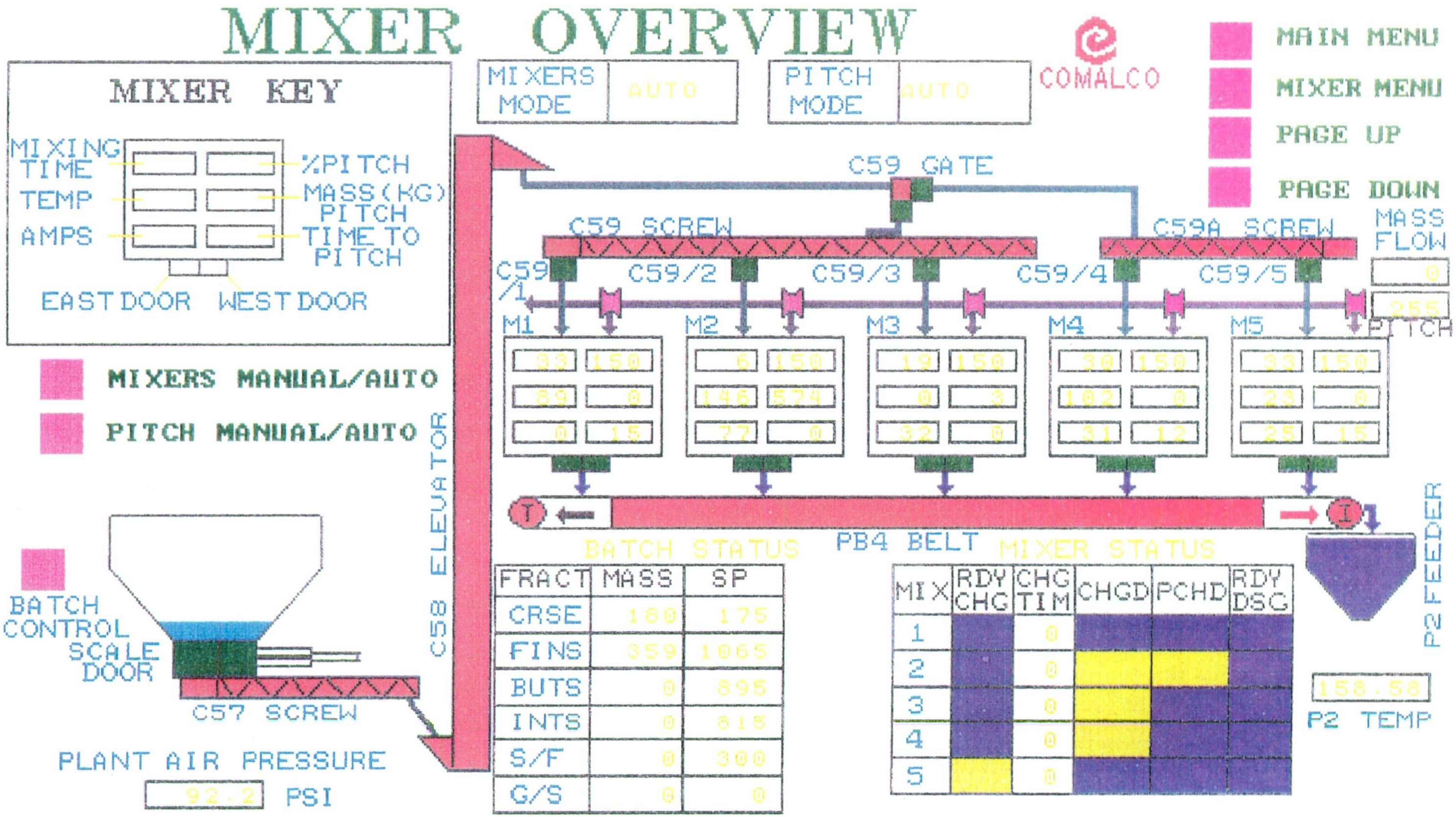
Turing A. (1950) *Computing Machinery and Intelligence*, Mind. 59, 433-460.

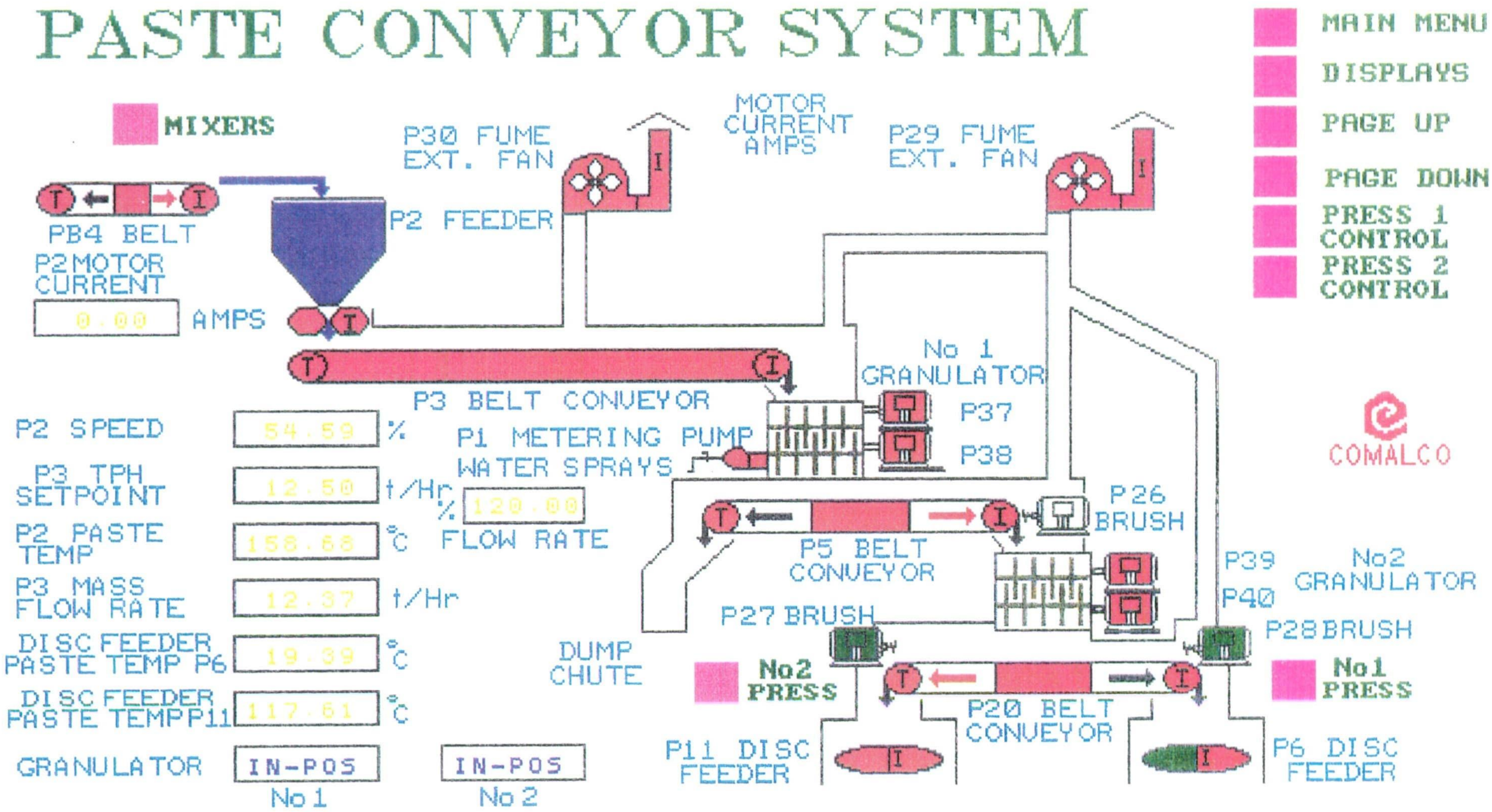
Villa L., Sierra C., Martine A.B. and Climent J. (1992), *Intelligent Process Control by Means of Expert Systems and Machine Vision* IEA/AIE *5th. International Conference.*

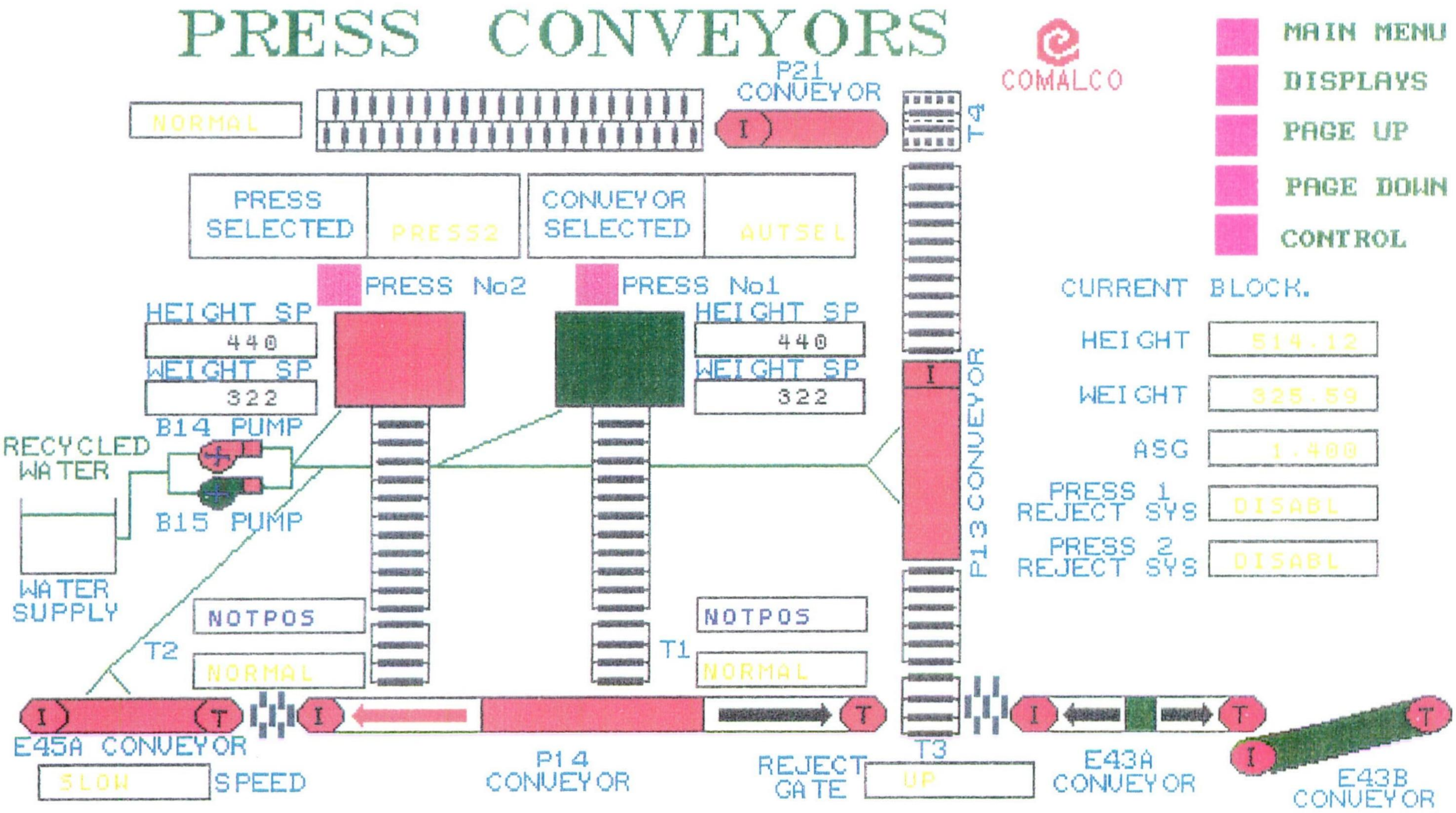
APPENDIX 1

Relevant Operator Station Displays of the Anode Production Process

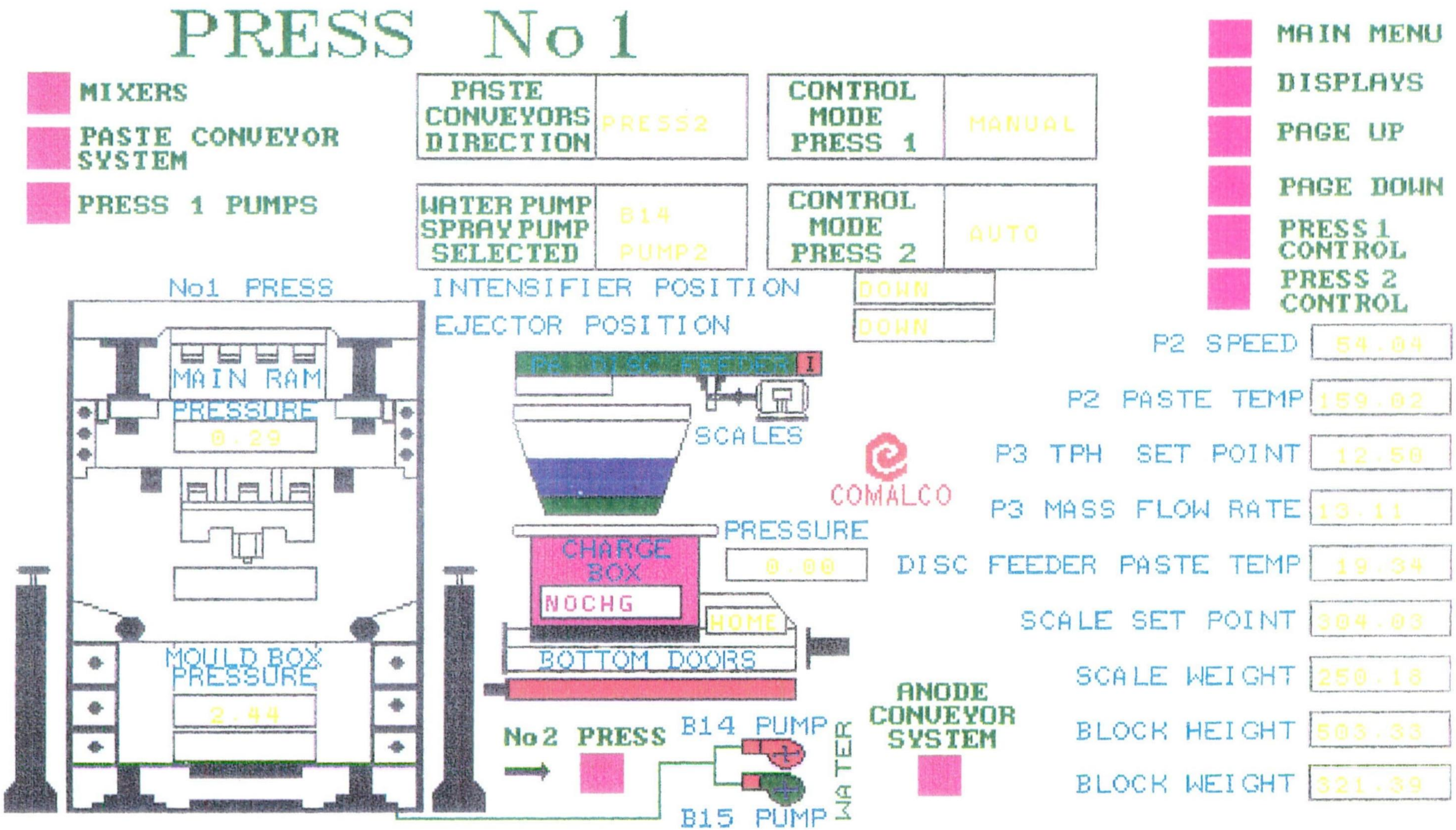

BALL MILL PRODUCTION
COMALCO
MAIN MENU
DISPLAYS
PAGE UP
PAGE DOWN
CONTROL
CONTROL MODE
AUTO
CBF3 DUST
DRYER DISPLAY
COKE CRUSHING
RADIAL FLOW CLASSIFIER
CYCLONE
BALL MILL FEED BIN 12T
40T COKE BIN
MAKE-UP GATE
C45A STAR VALUE
B/MILL RETURN
2.60
t/Hr
C48 STAR VALUE
RAW COKE
OVERSIZE
FINES
AIR
C34 VIBRO
COKE CRUSHING
C49 SCREW
C50 SCREW
No2VISCO DUST COLLECTOR
DCE VOKES DUST COLLECTOR
12T FINES BINS
C44 DISC FEEDER
B/MILL FEED
10.55
t/Hr
C45 SCREW
306 Amps
C53 LUBE PUMP
C46 KVS BALL MILL
C47 EXHAUST FAN
120
Amps
No1
No2
No3
No4
C52 LIFT PUMP
C51 LIFT PUMP
FINES PRODUCTION
6.21
t/Hr
MIXING DISPLAY


MIXER OVERVIEW
MIXER KEY
MIXING TIME
TEMP
AMPS
%PITCH
MASS(KG) PITCH
TIME TO PITCH
EAST DOOR
WEST DOOR
MIXERS MODE
AUTO
PITCH MODE
AUTO
COMALCO
MAIN MENU
MIXER MENU
PAGE UP
PAGE DOWN
MIXERS MANUAL/AUTO
PITCH MANUAL/AUTO
C58 ELEVATOR
C59 GATE
C59 SCREW
C59A SCREW
MASS FLOW
0
255
PITCH
C59/1
C59/2
C59/3
C59/4
C59/5
M1
33 150
89 0
0 15
M2
6 150
146 574
77 0
M3
19 150
0 3
32 0
M4
30 150
102 0
31 12
M5
33 150
23 0
25 15
PB4 BELT
P2 FEEDER
158.58
P2 TEMP
BATCH CONTROL
SCALE DOOR
C57 SCREW
PLANT AIR PRESSURE
92.2 PSI
BATCH STATUS
FRACT MASS SP
CRSE 180 175
FINS 359 1065
BUTS 0 895
INTS 0 815
S/F 0 300
G/S 0 0
MIXER STATUS
MIX RDY CHG CHG TIM CHGD PCHD RDY DSG
1 0
2 0
3 0
4 0
5 0


PASTE CONVEYOR SYSTEM
MAIN MENU
DISPLAYS
PAGE UP
PAGE DOWN
PRESS 1 CONTROL
PRESS 2 CONTROL
MIXERS
P30 FUME EXT. FAN
MOTOR CURRENT AMPS
P29 FUME EXT. FAN
PB4 BELT
P2 FEEDER
P2 MOTOR CURRENT
0.00
AMPS
P3 BELT CONVEYOR
No 1 GRANULATOR
P37
P38
P1 METERING PUMP
WATER SPRAYS
P2 SPEED
54.59
%
P3 TPH SETPOINT
12.50
t/Hr
%
120.00
FLOW RATE
P2 PASTE TEMP
158.68
°C
P3 MASS FLOW RATE
12.37
t/Hr
DISC FEEDER PASTE TEMP P6
19.39
°C
DISC FEEDER PASTE TEMP P11
117.61
°C
GRANULATOR
IN-POS
No 1
IN-POS
No 2
P26 BRUSH
P5 BELT CONVEYOR
P39
P40
No2 GRANULATOR
P27 BRUSH
P28 BRUSH
DUMP CHUTE
No2 PRESS
No1 PRESS
P20 BELT CONVEYOR
P11 DISC FEEDER
P6 DISC FEEDER
COMALCO



PRESS CONVEYORS
COMALCO
MAIN MENU
DISPLAYS
PAGE UP
PAGE DOWN
CONTROL
NORMAL
P21 CONVEYOR
T4
PRESS SELECTED
PRESS2
CONVEYOR SELECTED
AUTSEL
PRESS No2
PRESS No1
HEIGHT SP
440
WEIGHT SP
322
HEIGHT SP
440
WEIGHT SP
322
CURRENT BLOCK.
HEIGHT
514.12
WEIGHT
325.59
ASG
1.400
PRESS 1 REJECT SYS
DISABL
PRESS 2 REJECT SYS
DISABL
P13 CONVEYOR
RECYCLED WATER
B14 PUMP
B15 PUMP
WATER SUPPLY
NOTPOS
NOTPOS
T2
T1
NORMAL
NORMAL
E45A CONVEYOR
SLOW
SPEED
P14 CONVEYOR
REJECT GATE
UP
T3
E43A CONVEYOR
E43B CONVEYOR


PRESS No1
MIXERS
PASTE CONVEYOR SYSTEM
PRESS 1 PUMPS
PASTE CONVEYORS DIRECTION
PRESS2
CONTROL MODE PRESS 1
MANUAL
WATER PUMP SPRAY PUMP SELECTED
B14
PUMP2
CONTROL MODE PRESS 2
AUTO
MAIN MENU
DISPLAYS
PAGE UP
PAGE DOWN
PRESS 1 CONTROL
PRESS 2 CONTROL
No1 PRESS
INTENSIFIER POSITION
DOWN
EJECTOR POSITION
DOWN
MAIN RAM
PRESSURE
0.29
P4 DISC FEEDER
SCALES
COMALCO
PRESSURE
0.00
CHARGE BOX
NOCHG
HOME
BOTTOM DOORS
MOULD BOX PRESSURE
2.44
No2 PRESS
B14 PUMP
B15 PUMP
WATER
ANODE CONVEYOR SYSTEM
P2 SPEED
54.84
P2 PASTE TEMP
159.82
P3 TPH SET POINT
12.50
P3 MASS FLOW RATE
13.11
DISC FEEDER PASTE TEMP
19.34
SCALE SET POINT
304.03
SCALE WEIGHT
250.18
BLOCK HEIGHT
503.33
BLOCK WEIGHT
321.39

APPENDIX 2

Program Classes and Attributes

CLASS Actions
- Put ON HOLD
- Continue processing
- Void
- Continue
- Show fault message
- Deal with messages
- View messages
- Get sql sel_ string
- Check ON HOLD
- Close files
- Get SOP file
- Print SOP file
- Continue from SOP
- Omit end of module routine
- Do sensor analysis
- Display SOP pushbutton
- Sensor problem
- Restart application
- Restart button
- Get test data

CLASS Ball Mill Data
- Start up time
- Started
- Running time
- Running minutes
- Fines production optimal
- Motor amps low
- Motor amps has been normal
- Fines used by calculation

CLASS Ball Mill Table Data
- Item name
- Value
- Comment

CLASS Blaine Index
- Value
- DTS
- Age

CLASS Current Message
- Time of message
- Message text

CLASS Mixer & Press Data
- Item
- Value
- Comment
- Cause
- Set point

CLASS CUSUM Chart
- CUSUM
- Mask positive
- Mask negative

CLASS Data
- Getting data
- Read time
- Determine trends
- Analyse anode weight data
- Analyse anode height data
- Analyse hopper weight data
- Analyse pitch level data
- Analyse GAD data
- Analyse AW minus HW data
- Analyse pressure data
- Analyse P2 temperature data
- Analyse press temperature data
- Analyse press sensors
- Request data ex Excel
- Get data
- Null value
- Analyse Ball Mill operation
- Anode production stopping
- Paste production stopping

CLASS Domain
- Intercept
- Temp_message
- sql__string_1
- sql__string_2
- sql__string_3
- newline
- Reading
- Counter
- Set_point
- Temp status
- Application counter
- i
- Fault found
- Comment message
- Title text
- Round off
- Cause message
- Error count
- Heading label
- Normal display time
- Actual display time

CLASS EWMA Chart
- UCL
- EWMA
- LCL

CLASS Mixers: Point IDs
- Motor
- Proportional valve
- Outlet temp SP

CLASS Mixer Batch
- Fin_DTS
- Coarse
- Fines
- Butts
- Inter
- Su_fines
- Pitch
- Batch weight
- Percentage pitch
- EWMA

CLASS Green Anode
- Height
- Weight
- GAD
- Hopper_wt
- Pr_temp
- Max_press
- DTS
- Weight difference
- CUSUM
- EWMA

CLASS Honeywell Point Average
- Point_ID
- Description
- Value
- Excel item

CLASS Honeywell Point Rate
- Point_ID
- Description
- Value
- Excel item

CLASS Honeywell Point Value
- Point_ID
- Description
- Value
- Excel item

CLASS Message_History
- Time_of_message
- Message_text

CLASS P_2 Temperature
- Fin_DTS
- Drop_tmp
- Mixer_no
- EWMA

CLASS Mixer Problems
- Low paste temperature
- High paste temperature
- Overheated paste
- Mixer number
- Paste temperature
- HOLD UP mode
- HOLD UP counter
- P2 temperature reading

CLASS No Data
- Anode message
- Anode comment
- Anode cause
- Batch message
- Batch comment
- Batch cause
- Common message
- No press data
- No mixer data
- No fines sieve data
- No data from NIF server
- No data from user table

CLASS Press Problems
- Possible paste temperature
- Spray pump running
- Air pressure OK
- Paste temperature
- High temp count
- Low temp count
- Anode weight sensor
- Hopper weight sensor
- Height sensor
- Anode weight reading
- Height reading
- Hopper weight reading
- Pressure
- Temperature

CLASS Process Variables ex db
- SetPoint
- SP_limit_width
- WarnDeltaValue
- AlarmValue
- Err_LowLmt
- Err_UpLmt
- Reading_span
- P1_GAD_Ht_Const
- P1_GAD_Const
- P2_GAD_Ht_Const
- P2_GAD_Const
- Value
- Warning time
- GAD_Ht_Const
- GAD_Const
- Mask_height

CLASS Sel_String
- sql_text_1
- sql_now
- sql_minute
- sql_hour
- sql_day
- sql_month
- sql_year
- sql_month
- sql_text_time
- sql_text_2
- sql_text_3

CLASS Shewhart Chart
- Reading
- Actual lower control limit
- Actual upper control limit
- Trend line
- Set point
- Lower SP
- Upper SP
- Lower limit
- Upper limit

CLASS Stats
- Instances
- Instance squared
- Mean instance
- Sum instance
- Sum instance squared
- Reading
- Instance times reading
- Mean reading
- Sum reading
- Sum instance X reading
- SSx
- SPxy
- Current trend value
- Slope
- Slope conversion factor
- Hourly change
- Intercept time
- Start DTS
- End DTS
- Readings time span
- Anode height slope
- Anode height intercept time
- Anode weight slope
- Anode weight intercept time
- Hopper weight intercept time
- Hopper weight slope
- Notional pr_temp
- Readings span in minutes
- Pitching level
- Lowest value
- Highest value
- Delta AW minus HW
- No paste temp
- Variation from target
- CUSUM
- Mean anode height
- Mean anode weight
- Mean hopper weight
- Mean anode minus hopper weight
- Mean GAD
- Mean pitch level
- Mean press pressure
- Mean press temperature
- Mean P2 temperature
- Mean range anode weight
- Mean range anode height
- Mean range hopper weight
- Mean range pitch
- Mean range GAD
- Mean range anode minus hopper weight
- Mean range pressure
- Mean range P2 temp
- Mean range press temp
- Variation
- Sum variation squared
- Standard deviation
- EWMA LCL
- EWMA UCL
- EWMA constant
- Last EMWA
- Mixer_fines weight
- Mixer_batch weight
- Press_batch weight
- Press_fines weight
- % fines
- Delta AW
- Delta HW
- GAD intercept time
- Delta height

CLASS Trend Analysis
- Set point
- Set point lower limit
- Set point upper limit
- Anode weight SP
- Anode height SP
- Property
- Plot a Shewhart charts
- Sample count
- GAD set point lower limit
- GAD set point upper limit
- Range
- Sum range
- Mean range
- Plot CUSUM & EWMA chart
- Mask height
- Mask length
- Shewhart control limit factor

APPENDIX 3

Appendix Table 3.1: Test Data for Press Parameters: Table *gc_anode* from Access file *press_2.mdb*

DTS	WEIGHT	HEIGHT	PR_TEMP	MAX_PRESS	HOPPER_WT
28/07/95 6:00:05	317.9	434.8	120.9	14.2	317.6
28/07/95 6:01:15	320.0	436.3	122.1	14.9	318.6
28/07/95 6:02:15	323.3	440.7	120.4	14.7	322.1
28/07/95 6:03:20	319.5	436.1	120.6	14.4	318.6
28/07/95 6:04:20	314.8	430.6	122.2	14.1	314.8
28/07/95 6:05:25	322.2	439.6	120.5	14.4	320.9
28/07/95 6:06:25	317.0	432.2	120.9	14.9	316.2
28/07/95 6:07:30	324.2	442.5	121.6	14.4	324.4
28/07/95 6:08:30	325.1	443.3	122.9	14.0	324.9
28/07/95 6:09:30	316.6	432.6	121.5	14.5	317.1
28/07/95 6:10:35	319.1	436.7	122.8	13.7	318.4
28/07/95 6:11:35	318.7	434.5	122.7	14.1	317.8
28/07/95 6:12:40	327.2	447.6	121.3	14.0	327.6
28/07/95 6:13:40	326.9	445.9	123.9	14.7	328.2
28/07/95 6:14:40	324.4	443.3	121.0	13.3	322.7
28/07/95 6:15:40	320.8	438.3	122.3	14.0	319.3
28/07/95 6:16:46	317.9	435.9	122.1	13.4	317.7
28/07/95 6:17:45	319.5	438.5	121.1	13.7	317.8
28/07/95 6:18:45	325.7	445.3	123.1	14.2	325.8
28/07/95 6:19:50	321.7	441.9	121.6	14.1	319.9
28/07/95 6:20:50	322.1	441.9	122.9	12.6	321.0
28/07/95 6:21:50	326.8	449.1	122.8	13.3	325.0
28/07/95 6:22:55	321.6	442.2	121.3	14.6	319.7
28/07/95 6:23:55	317.5	436.5	124.4	13.8	317.6
28/07/95 6:24:55	318.7	438.4	122.5	14.0	319.7
28/07/95 6:26:00	327.6	451.5	121.5	13.6	325.9
28/07/95 6:27:00	324.3	444.8	124.4	13.6	326.1
28/07/95 6:28:00	318.7	438.9	121.0	13.5	317.2
28/07/95 6:29:05	320.8	440.2	122.2	14.4	321.7
28/07/95 6:30:05	321.2	446.4	122.1	13.9	320.9
28/07/95 6:31:05	324.2	451.3	119.7	14.3	322.1
28/07/95 6:32:05	319.6	444.0	121.6	14.1	318.9
28/07/95 6:33:10	324.2	451.2	123.3	13.8	322.2
28/07/95 6:34:10	330.5	458.8	120.6	13.5	329.4
28/07/95 6:35:15	324.6	450.0	122.7	14.4	323.2
28/07/95 6:36:15	322.9	449.3	122.6	14.0	322.8
28/07/95 6:37:15	319.0	443.3	120.8	13.8	318.4
28/07/95 6:38:20	326.0	453.0	123.5	13.9	326.5
28/07/95 6:39:20	324.6	453.1	122.0	13.6	323.4
28/07/95 6:40:25	326.6	454.5	120.2	14.8	325.4
28/07/95 6:41:25	319.1	443.4	122.7	13.6	317.7
28/07/95 6:42:25	320.4	441.3	121.8	14.4	319.0
28/07/95 6:44:15	325.4	445.9	121.2	14.3	324.7
28/07/95 6:45:15	319.0	436.3	122.2	14.1	318.4
28/07/95 6:46:15	326.4	447.8	120.7	13.7	325.8
28/07/95 6:47:20	328.0	449.1	121.4	14.2	326.9
28/07/95 6:48:20	322.6	440.9	123.0	14.4	322.1

DTS	WEIGHT	HEIGHT	PR_TEMP	MAX_PRESS	HOPPER_WT
28/07/95 6:49:20	318.3	435.7	120.7	14.2	318.6
28/07/95 6:50:25	324.2	445.1	121.5	14.2	323.4
28/07/95 6:51:25	325.1	445.5	122.6	13.4	326.4
28/07/95 6:52:25	324.6	442.7	119.9	13.8	324.7
28/07/95 6:53:30	320.0	438.1	120.3	13.6	319.5
28/07/95 6:54:30	316.2	434.0	120.5	14.2	316.5
28/07/95 6:55:30	319.5	437.2	120.4	14.1	317.7
28/07/95 6:56:35	324.7	444.0	121.5	14.2	324.7
28/07/95 6:57:35	320.7	438.3	122.9	13.3	320.9
28/07/95 6:58:40	317.4	433.5	121.4	14.0	317.8
28/07/95 6:59:40	314.8	431.2	122.3	14.0	316.0
28/07/95 7:00:40	324.7	443.8	122.1	14.0	324.9
28/07/95 7:01:45	329.3	450.4	120.7	14.5	327.0
28/07/95 7:05:50	325.1	443.9	122.2	14.7	324.9
28/07/95 7:07:10	323.7	454.7	123.5	13.1	323.4
28/07/95 7:11:45	124.7	478.3	90.5	14.2	309.9
28/07/95 7:16:10	314.1	438.1	92.3	13.7	312.5
28/07/95 7:17:15	320.0	449.7	77.6	13.8	319.9
28/07/95 7:18:20	320.4	444.9	89.9	13.4	319.2
28/07/95 7:19:25	315.3	440.7	107.4	13.2	314.4
28/07/95 7:20:25	323.8	449.5	104.1	13.6	322.8
28/07/95 7:21:35	317.9	440.1	110.7	14.7	317.6
28/07/95 7:22:45	322.6	448.2	114.1	13.5	323.3
28/07/95 7:23:55	321.2	445.8	117.0	13.6	320.6
28/07/95 7:26:20	318.8	443.1	122.7	14.3	318.6
28/07/95 7:29:50	318.3	440.5	123.2	13.9	317.7
28/07/95 7:33:00	322.9	445.1	120.3	14.5	322.7
28/07/95 7:34:00	317.9	443.3	77.9	13.8	318.3
28/07/95 7:35:05	325.3	447.6	88.3	14.2	324.7
28/07/95 7:36:05	324.2	446.4	100.6	13.7	324.1
28/07/95 7:37:15	319.2	439.4	108.6	14.3	319.4
28/07/95 7:38:25	318.0	436.4	115.8	13.7	317.7
28/07/95 7:39:45	318.4	437.2	120.5	14.6	319.2
28/07/95 7:40:55	323.4	445.5	122.4	13.7	323.3
28/07/95 7:42:00	321.7	439.8	120.3	14.7	321.2
28/07/95 7:43:10	322.2	443.4	123.6	14.0	321.6
28/07/95 7:44:30	325.5	447.0	120.9	14.5	324.3
28/07/95 7:44:51	317.0	434.8	122.8	14.5	317.7
28/07/95 7:46:55	317.0	432.1	123.3	13.2	317.7
28/07/95 7:48:40	315.5	430.5	123.2	14.2	315.8
28/07/95 7:49:25	322.9	438.6	121.6	14.4	321.1
28/07/95 7:50:25	326.8	443.7	125.2	14.0	326.3
28/07/95 7:51:25	317.9	433.6	123.8	14.4	317.6
28/07/95 7:52:30	319.5	435.5	122.2	12.8	319.2
28/07/95 7:53:30	322.9	439.8	122.4	13.8	323.1
28/07/95 7:54:30	324.5	442.3	123.3	13.4	323.3
28/07/95 7:55:35	316.5	432.3	121.6	14.1	317.2
28/07/95 7:56:35	322.1	438.4	124.4	13.8	320.9
28/07/95 7:57:35	318.8	435.4	121.4	13.8	319.0
28/07/95 7:58:40	318.4	433.8	121.5	14.8	317.6
28/07/95 7:59:40	322.1	438.0	125.1	14.2	321.5

DTS	WEIGHT	HEIGHT	PR_TEMP	MAX_PRESS	HOPPER_WT
28/07/95 8:00:45	326.8	444.7	123.3	14.9	326.3
28/07/95 8:01:45	322.2	438.6	121.9	12.5	320.3
28/07/95 8:02:45	322.9	439.3	125.3	13.7	323.2
28/07/95 8:03:45	322.7	439.8	124.2	14.0	323.2
28/07/95 8:04:50	324.3	441.2	122.5	13.3	323.4
28/07/95 8:05:50	328.4	446.8	123.1	14.3	327.6
28/07/95 8:06:50	320.3	436.6	123.8	13.7	319.7
28/07/95 8:07:50	319.6	435.8	122.8	13.6	319.7
28/07/95 8:08:55	318.3	434.6	122.6	14.1	317.7
28/07/95 8:09:55	322.1	440.7	121.9	14.1	322.2
28/07/95 8:10:55	322.9	442.6	123.3	13.4	322.2
28/07/95 8:11:55	317.8	435.0	123.5	14.1	316.6
28/07/95 8:13:00	316.5	434.6	122.2	14.1	315.8
28/07/95 8:14:00	323.3	442.8	122.7	14.0	322.1
28/07/95 8:15:00	322.9	443.3	123.9	13.8	323.3
28/07/95 8:16:00	328.4	450.1	123.3	14.7	327.0
28/07/95 8:17:05	320.8	438.6	122.6	14.2	320.1
28/07/95 8:18:06	327.6	450.5	122.6	13.7	326.9
28/07/95 8:19:05	319.0	439.2	123.6	13.5	320.3
28/07/95 8:20:11	322.5	442.4	122.4	14.4	323.1
28/07/95 8:21:10	322.3	442.7	122.0	13.7	320.6
28/07/95 8:22:10	322.1	441.4	122.3	14.1	320.9
28/07/95 8:23:15	321.3	440.5	122.6	14.2	321.1
28/07/95 8:24:15	323.8	445.5	121.5	13.5	324.9
28/07/95 8:25:15	324.6	446.0	124.0	13.8	325.4
28/07/95 8:26:15	330.1	453.7	122.4	13.9	330.5
28/07/95 8:27:20	316.7	435.3	122.2	14.2	317.5
28/07/95 8:28:20	323.3	444.5	124.1	13.9	323.3
28/07/95 8:29:25	318.3	437.6	121.6	13.6	318.1
28/07/95 8:30:25	315.7	434.6	123.5	13.9	316.6
28/07/95 8:31:25	325.1	447.6	123.6	13.1	325.8
28/07/95 8:34:40	320.0	439.1	120.7	14.0	319.3
28/07/95 8:35:40	320.8	447.2	122.7	13.9	321.0
28/07/95 8:36:45	327.2	446.7	93.8	14.8	328.3
28/07/95 8:37:45	317.6	434.7	105.9	14.4	319.0
28/07/95 8:38:45	328.9	449.4	114.1	14.6	328.3
28/07/95 8:40:40	329.7	450.2	119.9	14.3	329.5
28/07/95 8:41:40	311.9	426.8	122.1	14.7	312.7
28/07/95 8:42:45	325.9	444.0	102.4	14.3	326.3
28/07/95 8:43:45	326.4	445.4	108.2	14.3	325.0
28/07/95 8:44:45	325.9	445.7	112.1	14.3	324.5
28/07/95 8:45:50	315.4	431.1	114.9	14.0	315.4
28/07/95 8:47:05	318.7	435.4	116.5	14.1	318.3
28/07/95 8:52:35	314.8	431.3	117.1	13.8	316.5
28/07/95 8:53:30	332.7	460.2	72.1	13.2	331.9
28/07/95 8:54:35	323.8	443.9	87.9	12.8	323.8
28/07/95 8:55:35	329.7	452.4	102.5	13.9	328.8
28/07/95 8:56:40	330.2	454.9	112.1	13.8	329.5
28/07/95 8:57:40	327.3	449.9	117.8	13.5	327.6
28/07/95 8:58:40	329.8	453.6	121.6	14.3	330.8

DTS	WEIGHT	HEIGHT	PR_TEMP	MAX_PRESS	HOPPER_WT
28/07/95 9:02:00	328.0	451.1	123.1	14.3	328.8
28/07/95 9:03:00	322.6	447.3	120.9	13.6	324.5
28/07/95 9:04:05	322.1	442.6	85.8	13.5	323.2
28/07/95 9:05:05	327.5	450.5	96.6	14.0	326.9
28/07/95 9:14:55	326.8	449.3	104.3	14.1	325.3
28/07/95 9:15:55	322.2	448.7	109.4	13.3	321.0
28/07/95 9:16:55	323.8	444.9	67.4	13.9	323.9
28/07/95 9:18:02	330.6	456.5	89.7	13.6	328.9
28/07/95 9:19:00	324.2	446.6	104.1	13.8	324.5
28/07/95 9:20:05	322.6	443.9	113.2	14.4	323.1
28/07/95 9:21:55	325.6	447.8	118.7	14.8	325.6
28/07/95 9:23:00	314.8	433.5	121.5	14.0	315.3
28/07/95 9:24:00	328.9	451.8	100.9	14.2	327.6
28/07/95 9:25:05	322.9	444.7	108.1	14.0	320.6
28/07/95 9:26:05	318.7	438.3	113.0	13.9	318.8
28/07/95 9:27:05	318.3	438.0	116.8	14.0	317.6
28/07/95 9:31:20	321.7	442.3	118.6	14.4	320.3

Appendix Table 3.2: Test Data for Mixer Parameters: Table *gc_batch* from Access file *press_2.mdb*

FIN_DTS	MIXER_NO	COARSE	FINES	BUTTS	INTER	SU_FINES	PITCH	DROP_TMP
28/07/95 5:51:18	5	522	1194	557	713	259	500	153.9
28/07/95 6:04:43	2	520	1214	548	705	265	502	156.7
28/07/95 6:16:43	3	522	1203	545	714	268	504	159.5
28/07/95 6:29:13	4	522	1204	545	710	280	505	156.1
28/07/95 6:40:42	5	522	1198	550	716	278	503	152.2
28/07/95 6:53:03	2	518	1197	554	717	271	502	154.5
28/07/95 7:08:23	3	518	1198	559	713	281	507	141.7
28/07/95 7:27:38	4	520	1194	554	717	262	503	162.7
28/07/95 7:44:48	5	519	1205	544	714	270	501	163.3
28/07/95 7:56:13	2	522	1208	548	708	256	506	165.7
28/07/95 8:08:13	3	525	1202	542	713	273	504	163.8
28/07/95 8:20:08	4	518	1214	536	714	270	505	161.7
28/07/95 8:37:53	5	540	1170	558	720	260	500	149.7
28/07/95 8:55:18	2	518	1201	556	710	269	502	151.9
28/07/95 9:17:58	3	518	1201	554	717	262	504	152.6

Appendix Table 3.3: Test Data for Blaine Index: Table *g_sieve* from Access file *g_sieve.mdb*

ENTRY_DTS	BLN_INDX
1/07/96 1:17:24	2021
1/07/96 1:19:47	1690
1/07/96 6:10:13	24221
1/07/96 6:11:31	22231
1/07/96 6:12:57	24170
2/07/96 6:59:38	2140
2/07/96 18:45:21	1967

Property Process parameter	Set_ Point	SP_Limit _Width	WarnDelta Value	Alarm Value	Err_ LowLmt	Err_ UpLmt	Reading _Span	Value	P1_GAD Ht_Const	P1_GAD _Const	P2_GAD Ht_Const	P2_GAD _Const	Mask_ Height
An_height		10			0.9	1.1							8
An_weight		7			0.9	1.1							8
AnWt_HopWt		3											8
GAD		40							0.000474	0.005147	0.000474	0.005147	8
Hop_weight		7			0.9	1.1							8
HTO_outlet_temp	245	20		270				265					
Mixer_temp		3		180	140	200							
P2_temp			10	180	140	200							5
Pitch_level		0.1											5
Pressure	14	1			12	16							8
Press_temp		3		130		135	0 0:20:00	5					8
Read_time							0 2:00:00						
Pause							0 0:00:30						

Appendix Table 3.4: Access Table *AnodeLimit* of User Defined Variables

APPENDIX 4

Paper delivered at ANZIIS-96 - 4th Australian and New Zealand Conference on Intelligent Information Systems held in Adelaide.

An Expert System Based Aid for Anode Optimisation

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ABSTRACT: This paper describes the first stage of the development of an expert system for monitoring the production process of anodes used in the smelting of aluminium. The expert system based on *Level5 Object* continually interrogates the process control system and provides on-line recommendations to operators of any problem which may affect the consistency and quality of anodes. The research has demonstrated the feasibility of using an expert system based software system to oversee a complex production process and to provide meaningful and timely information to the operator to enable the application of corrective action to the process if required.

Keywords: Control system, expert system, operational aid, production, Level5 Object.

1. INTRODUCTION

Modern computer based management systems coupled with Supervisory, Control and Data Acquisition (SCADA) systems make it possible to change the process control structure of large production plants [1], [2] and [3]. Previously, production areas within these plants were run by a supervised team of twenty or more operators. Now such plants can be controlled by just four operators without direct supervision.

One of the important aspects of the process under control is to provide a consistent quality of the anodes used in the smelting of aluminium. It requires knowledge and experience from operators. However, even experienced operators cannot always predict a problem before that problem develops and thus produce anodes of a consistent and high quality. Meanwhile, even a small increase of the mean life time of the anode may lead to a significant decrease of the plant operational cost. There is thus a financial incentive for an on-line intelligent system advising of the onset of a problem before that problem occurs. Such a system would provide operators with the opportunity to take timely actions and thus prevent failures in the anode production process.

2. THE ANODE PRODUCTION PROCESS

In the smelting of aluminium, a DC current in excess of 90,000A at 4.5V is passed between a cathode and anode across a molten bath of alumina and catalysing additives in an electrolytic cell. The anode is sacrificial and consumed by the electrolytic process. The longer an anode can be left in a cell before being replaced, the lower the operational cost relating to its use. Typically, an anode is replaced every 15 days. In a smelter producing 100,000t of aluminium per year, 550 anodes are changed every day. The anodes are changed on a fixed rota based on the expected anode life, even though some anodes of higher quality could be retained. Thus, if all anodes were produced with physical and chemical properties of a consistent high quality, the expected mean life, and therefore the changing rota, could be increased. This would lead to a reduction in the operational cost of producing anodes.

An anode is a conglomerate of variously sized coke particles, coke fines and liquid pitch that has been mixed in a heated mixer and then formed into blocks in a press. The Carbon Plant, comprising storage bins, screens, coke driers, crushers, conveying equipment, mixers, presses, dust collectors, weigh scales, heat transfer oil heaters, liquid pitch heating and handling facilities is operated through programmed logic controllers using data provided by the Honeywell SCADA system. The computer screens show the current state of each stage of the process, ie actual paste temperatures, bin levels, scale weights, anode weight and height, status and direction of conveyors, percentage opening of heating oil control valves, etc. The Honeywell SCADA system polls the status of 1800 points at intervals varying from 1 to 60 sec.

The area of concern of this paper relates to paste mixing and anode forming, as research has indicated high variation in these processes. There are five mixers, one of which is on stand-by. Coke, fines and liquid pitch are fed into each mixer in sequence in measured quantities in accordance to a recipe. Each mixer is heated with hot oil passing through the outer mixer jacket and through the mixing paddle. The temperature of the paste in the mixer and of the heat transfer oil at various points in the system are measured. A mixer discharges a batch of paste onto a conveyor that transfers that paste to the press. There, the paste is weighed in a scale that tares off, its temperature measured, and discharged into the press mould. A formed anode is ejected, its height and weight measured and sent to the next stage of the process by conveyor. Anodes of height outside the set limits are automatically rejected to scrap. A diagram of the process is shown in Figure 1.

Key parameters are the Green Apparent Density, calculated from the measured weight and height, temperature of the paste leaving a mixer and entering the press mould, percentage of pitch in any batch and the press pressure applied to form the anode.

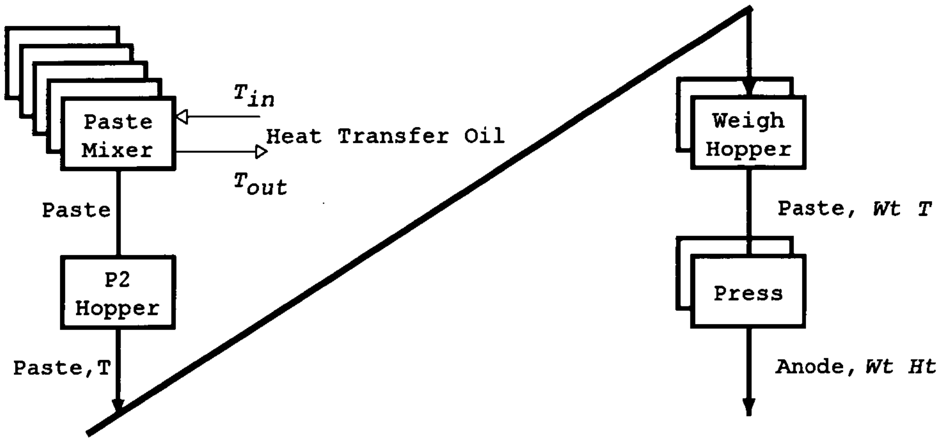

Figure 1. Schematic diagram of the anode production process.

3. STRUCTURE OF THE EXPERT SYSTEM

Using rule-based and object-oriented programming techniques[4], an expert system was developed around three basic functions, namely:

- Carry out a trend analysis of each of the process variables.
- From the analysis, identify problems in the anode production process and determine the cause of the problem via the Network Interrogation Facility server.
- Display charts and messages to an operator.

The general structure of the expert system based process monitor is illustrated in Figure 2.

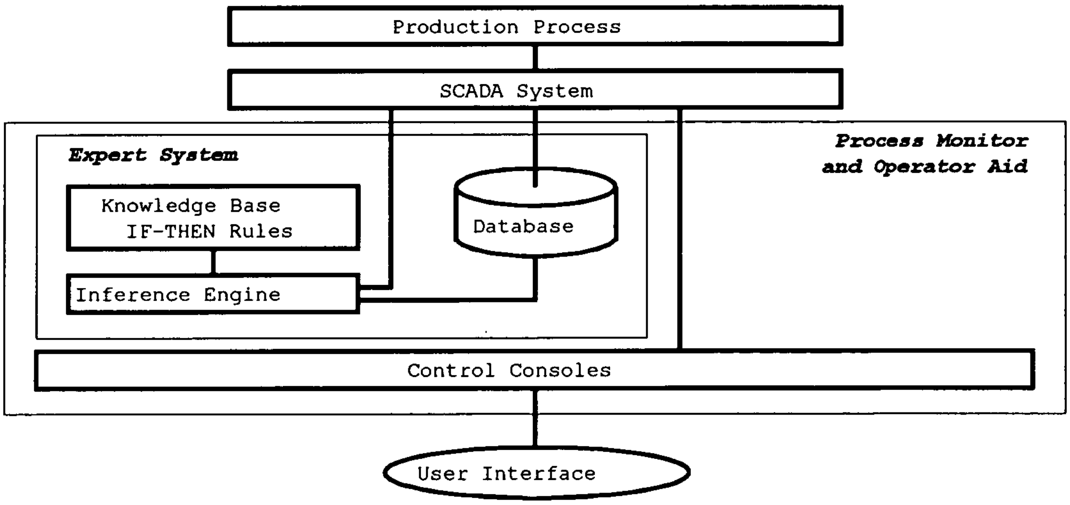

Figure 2. The general structure of the process monitor and operator aid.

4. ASSEMBLY AND DISPLAY OF DATA

4.1 Process Parameters

The Level5 Object based expert system uses three types of process parameters:

- control set points and actual process variables stored in the SCADA Access database,
- desirable set points and parameters input by the user into the USER database,
- instantaneous point values obtained through the Network Interrogation Facility (NIF) server and stored in an Excel spreadsheet.

Process parameters and set points are input into the SCADA system manually, eg the set point for the weigh hopper, while actual process variables are generated by the operation itself, eg the actual weight of paste discharged from the weigh hopper. The control set points are used by the SCADA system to control the process either directly or through feed-back loops. The SCADA system sends data to the database as required and designed into the system. For instance, though the point value of the weigh hopper weight is being polled every second to show the hopper filling on the monitor, the actual hopper weight sent to the database is the maximum value. Thus, the SCADA database contains a history of all point values sent to the database for the previous month.

Other set points are desirable values to be met that might be attained by manually changing control set points or might indicate problems if not attained. The Green Anode Density of an anode is an example of this type of set point. These values are not in the SCADA generated database but are manually input into the USER database of such process variables. Other variables input into the USER database are those used by the expert system that the user might wish to change without having to change the program.

The third type of process variable are the instantaneous point values polled by the NIF server, where a point value is the value of a specific attribute, eg direction of conveyor, pump ON/OFF, paste temperature, percentage closure of valve, etc. If it is necessary to keep track of the movement of a point value, such as position of a flow control valve or bin or tank level, then these values are read into an array in the main application by a link with the Excel spreadsheet.

4.2 Basic Data

The basic data for the whole analysis is obtained from seven process variables generated in the two hours (a user input variable) prior to running the application through one cycle of the analysis. This data is read from the SCADA generated database. These variables are: mixer paste temperature, percentage pitch, paste weight, press paste temperature, anode weight, anode height and press pressure. If the plant is running properly, there are 15 values of the first two variables and in excess of 100 of the remaining variables in the two hour window. From these variables are generated two further variables, anode weight minus paste weight and Green Apparent Density, that provides valuable information about the process. Data that is deemed erroneous (as defined ex the USER data base), for being too high or low or for being duplicated, are excluded.

In turn, the data for each variable is statistically trended and displayed in chart form showing actual readings, set point line, upper and lower set point limits, trend line and actual upper and lower operating limits for groups of readings. Messages relating to the trends and analysis are displayed below the chart. These messages are also sent to the USER database for later retrieval if required. The chart and accompanying messages remain on the screen for up to 30sec, which feature can be overwritten by the user clicking on a pushbutton to pass onto the analysis of the next variable or hold the existing chart for further study or printing.

At the end of this trend analysis phase, which takes about eight minutes, the cycle repeats itself with the SCADA database being accessed again to collect the most recent data. The charts, so displayed, provide a useful means of quickly viewing the critical process variables as they are occurring.

5. POSSIBLE PROCESS PROBLEMS

The foregoing analysis is essential for determining whether or not problems exist in the anode production process. Generally, problems with sensors are detected by analysing trends while problems associated with equipment are resolved by determining point values through the NIF server.

5.1 Sensors

The analysis determines trends of positive, negative or zero slope with respect to the upper and lower set point limits of each of the process variables under investigation, as displayed in Figure 3.

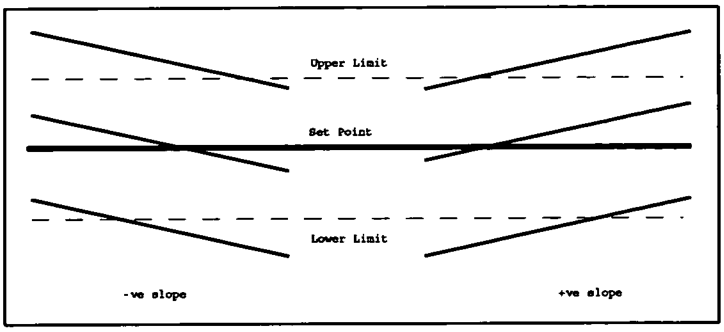

Figure 3. Trend versus Process Limits.

Theoretically, the paste weight in the weigh hopper prior to the press mould should be the same as the weight of the anode pressed from said paste. Any major difference between these two weights indicates a problem either with the weigh hopper sensor or with the anode weight sensor. Furthermore, there is a direct relationship between the anode height, the anode weight and the paste weight. As the paste weight increases, so should the anode weight and anode height. The mean value of the Green Apparent Density (GAD) in relation to its set point provides an additional check on a sensor reading. Thus, a truth table, shown in Figure 4, can be compiled comparing trends of these variables in order to arrive at possible sensor or set point problems.

GAD	Anode Trend Slopes			Delta Weight*	Problem
	Anode Weight	Hopper Weight	Anode Height		
OK	+'ve	+'ve	+'ve		Hopper weight set point
	-'ve	-'ve	-'ve		Hopper weight set point
	+'ve	-'ve	+'ve		Hopper weight sensor
	-'ve	+'ve	+'ve		Anode weight sensor
	+'ve	+'ve	-'ve	<limit	Anode height sensor
	+'ve	+'ve	-'ve	>limit	Height and hopper weight sensors
	-'ve	-'ve	+'ve	<limit	Anode height sensor
	-'ve	-'ve	+'ve	>limit	Height and hopper weight sensors
	+'ve	-'ve	-'ve		Anode weight sensor
	-'ve	+'ve	-'ve		Hopper weight sensor
Low				<limit	Anode height sensor reading high
				>limit	Anode weight sensor reading low
High				<limit	Anode height sensor reading low
				>limit	Anode weight sensor reading high

* Delta weight = process limit for anode weight minus hopper weight

Figure 4. Truth table for anode sensor problems.

5.2 Mixer Paste Temperature Problems

The temperature of the paste entering the press mould has to be maintained within tight limits, else the anode will collapse or break up during conveyor transfer. Thus, the temperature in the mixer must be closely monitored and controlled.

Some of the reasons for paste temperature in a mixer being high are:
- Proportional heat transfer oil (HTO) flow valve on mixer stuck;
- Mixer HTO outlet temperature set point > HTO temperature set point.

- A mixer HTO outlet valve stuck fully open;
- HTO outlet temperature too high;
- System in HOLD-UP mode, ie discharge conveyor stopped and all proportional HTO flow valves shut.

Some of the reasons for paste temperature in a mixer being low in a mixer are:
- Proportional HTO flow valve on that mixer stuck;
- HTO outlet temperature set point too low;
- HTO pump not running;
- Coke drier not working;
- Vent (to extract dust or pitch fumes when charging) to vacuum system stuck open.

5.3 Press Paste Temperature Problems

Some of the reasons for the temperature of the paste entering the press mould being high are:
- Paste from mixer too hot;
- Paste cooling spray pump not running;
- Fan providing air cooling not running;
- Water spray air pressure low;
- No water flow to sprays;
- Spray head blocked or damaged.

6. EXPERT SYSTEM DEVELOPMENT

6.1 Software and Hardware

Level5 Object was chosen on the grounds of prior use by the writers and client, it being relatively inexpensive and its incorporation of facilities (ie ODBC and DDE) to talk to databases and other applications. The current limiting factor is the speed of accessing SCADA direct, wherein the speed is determined by the polling speed of the NIF (Network Interrogation Facility) server. This limiting factor has been somewhat mitigated by running two applications, the main application incorporating the knowledge and rule base and a slave application working in the background that interrogates SCADA and transfers point values to an Excel spreadsheet. The main application then interrogates the Excel file for the latest applicable data. Currently, a program is being developed to talk direct to a point in the control system, thus by-passing the NIF server.

The first year of development was carried out on realistic, but non-live data, on a stand-alone 486 PC with 8 Mb of RAM in Windows 3.1. Currently, further development is being carried out on a PC with Windows NT connected to the Plant's network by modem. The NT environment is required because of the number of applications running at the same time, ie the main *Level5* application holding conversations with another Level5 application and Excel and Access files

6.2 Knowledge Base

The knowledge base formally sets out rules derived from the truth table shown in Figures 3 and 4 and derived from the problems defined in Section 5.

6.3 Testing

Development has been predominantly carried out on realistic, but non-live data. Periodically, the application was run on the plant network on live data, accessing the SCADA database and NIF server. Thus, the rule base was modified to deal with real data and modified in line with user requirements. The application was developed to properly hold conversations with databases, SCADA and plant control systems over the network. The latter exposed many problems not obvious on a stand-alone PC.

Testing was also carried out by running the application continuously. While some failures were caused by faulty programming, which were fixed, others were caused by shortcomings in the *Level5 Five* software, which were worked around. This aspect of testing proved to be very time consuming. Reliability has improved from a mean time between failures of 1 hour to 80 hours.

7. CONCLUSION

An expert system has been developed to monitor and optimise a complex process of anode production on an aluminium plant. The expert system interacts with the SCADA system in real-time, applies rules from the knowledge base and advises operators how to optimise the production process in order to obtain anodes of consistent and high quality.

The research has demonstrated the feasibility of using an expert system based software system to oversee a complex production process, to analyse large amounts of data and to provide meaningful and timely information to the operator to enable the operator to take any necessary corrective action required.

While *Level5 Object* is a useful development tool and probably adequate for one-off type enquiries, there is a big question mark as to its robustness to continuously monitor a process. It is possible that the application will require hard coding, or transferring to a more powerful shell such as G2, for use in the production environment.

It is proposed to develop the application further to other areas of the Carbon Plant and to show Standard Operating Procedures in hypertext format as an aid to operators when responding to process problems.

8. ACKNOWLEDGMENTS

This research was funded under a grant from Comalco Aluminium (Bell Bay) Ltd.
The authors are grateful for the help provided by process specialists at Comalco, namely, P.W. Sulzberger, M. Hughes and S. Hancock.

9. REFERENCES

[1] D.T. Pham, *Expert Systems in Engineering*, 1988: J.C. Taunton & D.W. Haspel *"The Application of Expert System Techniques in On-Line Process Control"*.

[2] L. Villa, C. Sierra, A.B. Martine and J. Climent, *"Intelligent Process Control by Means of Expert Systems and Machine Vision"* 5th. International Conference, IEA/AIE-92.

[3] M.L. Mavrovouniotis, *"Artificial Intelligence in Process Engineering"*, (San Diego: Academic Press, 1990): D.R. Myers, J.F. Davis and C.H. Hurley II, *"An Expert System for Diagnosis of a Sequential, PLC-Controlled Operation"*.

[4] E.C. Payne and R.C. McArthur, "Developing Expert Systems", (New York: John Wiley & Sons, 1990).

APPENDIX 5

Paper delivered at ACIS '96 - The Seventh Australasian Conference on Information Systems, 1996 held in Hobart.

An Expert System Based Aid for Anode Optimisation

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ABSTRACT

This paper describes the first stage of the development of an expert system for monitoring the production process of anodes used in the smelting of aluminium. The expert system based on *Level5 Object* continually interrogates the process control system and provides on-line recommendations to operators of any problem which may affect the consistency and quality of anodes.

The research has demonstrated the feasibility of using an expert system based software system to oversee a complex production process and to provide meaningful and timely information to the operator to enable the application of corrective action to the process if required.

Keywords: Control system, expert system, operational aid, production, Level5 Object.

1. INTRODUCTION

Modern computer based management systems coupled with Supervisory, Control and Data Acquisition (SCADA) systems make it possible to change the process control structure of large production plants (IEA/AIE 1992, Mavrovouniotis 1990 and Pham 1988). Previously, production areas within these plants were run by a supervised team of twenty or more operators. Now such plants can be controlled by just four operators without direct supervision.

One of the important aspects of the process under control is to provide a consistent quality of the anodes used in the smelting of aluminium. It requires knowledge and experience from operators. However, even experienced operators cannot always predict a problem before that problem develops and thus produce anodes of a consistent and high quality. Meanwhile, even a small increase of the mean life time of the anode may lead to a significant decrease of the plant operational cost. There is thus a financial incentive for an on-line intelligent system advising of the onset of a problem before that problem occurs. Such a system would provide operators with the opportunity to take timely actions and thus prevent failures in the anode production process.

2. THE ANODE PRODUCTION PROCESS

In the smelting of aluminium, a DC current in excess of 90,000A at 4.5V is passed between a cathode and anode across a molten bath of alumina and catalysing additives in an electrolytic cell. The anode is sacrificial and consumed by the electrolytic process. The longer an anode can be left in a cell before being replaced, the lower the operational cost relating to its use. Typically, an anode is replaced every 15 days. In a smelter producing 100,000t of aluminium per year, 550 anodes are changed every day. The anodes are changed on a fixed rota based on the expected anode life, even though some anodes of higher quality could be retained. Thus, if all anodes were produced with physical and chemical properties of a consistent high quality, the expected mean life, and therefore the changing rota, could be increased. This would lead to a reduction in the operational cost of producing anodes.

An anode is a conglomerate of variously sized coke particles, coke fines and liquid pitch that has been mixed in a 4t mixer and then formed into blocks in a press. The Carbon Plant, comprising storage bins, screens, coke driers, crushers, conveying equipment, mixers, presses, dust collectors, weigh scales, heat transfer oil heaters, liquid pitch heating and handling facilities is operated through programmed logic controllers using data provided by the Honeywell SCADA system. The computer screens show the current state of each stage of the process, ie actual paste temperatures, bin levels, scale weights, anode weight and height, status and direction of conveyors, percentage opening of heating oil control valves, etc. The Honeywell SCADA system polls the status of 1800 points at intervals varying from 1 to 60 sec.

The area of concern of this paper relates to fines preparation, paste mixing and anode forming, as research has indicated high variation in these processes, variations that critically affect the properties of the anode.

The amount and sizing of the fines is one of these critical factors affecting the physical properties of an anode. Fines are made by grinding coke in a ball mill, which process is very sensitive to changes in process variables. Two criteria have to be met in producing fines, namely, a product of specified sizing in the Blaine Index range of 2000 to 2400 at a minimum rate of 8t/h. The Ball Mill is fed from a 12t bin containing the undersized material from a multi-stage screening process and from return oversize material from the ball mill operation itself. The value of the ball mill motor current provides a useful measure of the efficiency of the milling process. At optimum efficiency the ball mill motor runs at a current between 300 and 320A. This value and that of the feed bin level, the feed rate, the product rate and return feed rate are available as point values polled by the NIF server. The values of the Blaine Index are determined manually every four hours and keyed into the data base.

There are five mixers, one of which is on stand-by. Coke, fines and liquid pitch are fed into each mixer in sequence in measured quantities in accordance to a recipe and mixed to form a paste. Each mixer is heated with hot oil passing through the outer mixer jacket and through the mixing paddle. The temperature of the paste in the mixer and of the heat transfer oil at various points in the system are measured. A mixer discharges a batch of paste onto a conveyor that transfers that paste to the press.

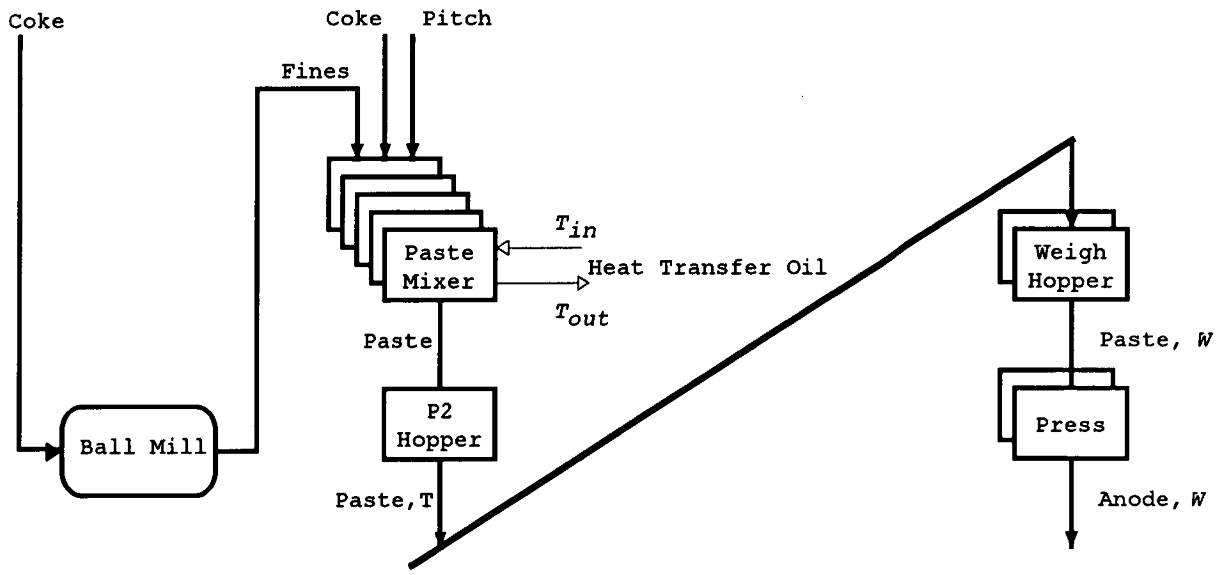

Figure 1. Schematic diagram of the anode production process.

There, the paste is weighed in a scale that tares off at about 325kg, its temperature measured, and discharged into the press mould. A formed anode is ejected, its height and weight measured and sent to the next stage of the process by conveyor. Anodes of height outside the set limits are automatically rejected to scrap. A diagram of the process is shown in Figure 1.

Key parameters are the Green Apparent Density, calculated from the measured weight and height, temperature of the paste leaving a mixer and entering the press mould, percentage of pitch in any batch and the press pressure applied to form the anode.

3. STRUCTURE OF THE EXPERT SYSTEM

The general structure of the expert system based process monitor and operator aid is illustrated in Figure 2.

Using rule-based and object-oriented programming techniques (Payne and McArthur 1990), an expert system was developed around three basic functions, namely:

- Carry out a trend analysis of each of the process variables.
- From the analysis, identify problems in the anode production process and determine the cause of the problem via the Network Interrogation Facility server.
- Display charts and messages to an operator.

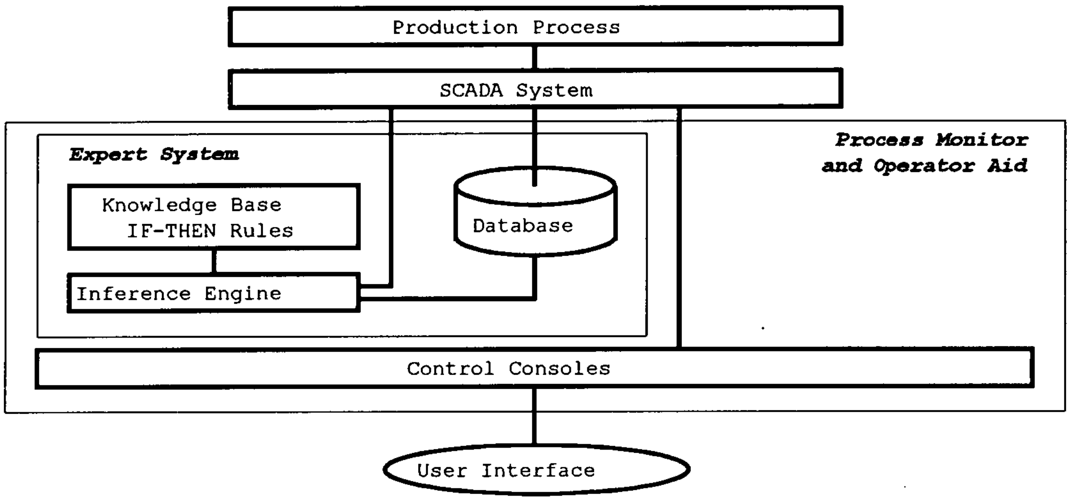

Figure 2. The general structure of the process monitor and operator aid.

4. ASSEMBLY AND DISPLAY OF DATA

4.1 Process Parameters

The Level5 Object based expert system uses three types of process parameters:

- control set points and actual process variables stored in the SCADA Access database,
- desirable set points and parameters input by the user into the USER database,
- instantaneous point values obtained through the Network Interrogation Facility (NIF) server and stored in an Excel spreadsheet.

Process parameters and set points are input into the SCADA system manually, eg the set point for the weigh hopper, while actual process variables are generated by the operation itself, eg the actual weight of paste discharged from the weigh hopper. The control set points are used by the SCADA system to control the process either directly or through feed-back loops. The SCADA system sends data to the database as required and designed into the system. For instance, though the point value of the weigh hopper paste weight (called hopper weight) is being polled every second to show the hopper filling on the monitor, the actual weigh hopper paste weight sent to the database is the maximum value. Thus, the SCADA database contains a history of all point values sent to the database for the previous month.

Other set points are desirable values to be met that might be attained by manually changing control set points or might indicate problems if not attained. The Green Anode Density of an anode is an example of this type of set point. These values are not in the SCADA generated database but are manually input into the USER database of such process variables. Other variables input into the USER database are those used by the expert system that the user might wish to change without having to change the program.

The third type of process variable are the instantaneous point values polled by the NIF server, where a point value is the value of a specific attribute, eg direction of conveyor, pump ON/OFF, paste temperature, percentage closure of valve, etc. If it is necessary to keep track of the movement of a point value, such as position of a flow control valve or bin or tank level, then these values are read into an array in the main application by a link with the Excel spreadsheet.

4.2 Basic Data

The basic data for the whole analysis is obtained from seven process variables generated in the two hours (a user input variable) prior to running the application through one cycle of the analysis. This data is read from the SCADA generated database. These variables are: mixer paste temperature, percentage pitch, hopper weight, press paste temperature, anode weight, anode height and press pressure. If the plant is running properly, there are 15 values of the first two variables and in excess of 100 of the remaining variables in the two hour window. From these variables are generated two further variables, anode weight minus hopper weight and Green Apparent Density, that provides valuable information about the process. Data that is deemed erroneous (as defined ex the USER data base), for being too high or low or for being duplicated, are excluded.

In turn, the data for each variable is statistically trended and displayed in chart form showing actual readings, set point line, upper and lower set point limits, trend line and actual upper and lower operating limits for groups of readings. Messages relating to the trends and analysis are displayed below the chart. These messages are also sent to the USER database for later retrieval if required. The chart and accompanying messages remain on the screen for up to 30sec, which feature can be overwritten by the user clicking on a pushbutton to pass onto the analysis of the next variable or hold the existing chart for further study or printing.

At the end of this trend analysis phase, which takes about eight minutes, the cycle repeats itself with the SCADA database being accessed again to collect the most recent data. The charts, so displayed, provide a useful means of quickly viewing the critical process variables as they are occurring.

5. POSSIBLE PROCESS PROBLEMS

The foregoing analysis is essential for determining whether or not problems exist in the anode production process. Generally, problems with sensors are detected by analysing trends while problems associated with equipment are resolved by determining point values through the NIF server.

5.1 Sensors

The analysis determines trends of positive, negative or zero slope with respect to the upper and lower set point limits of each of the process variables under investigation, as displayed in Figure 3.

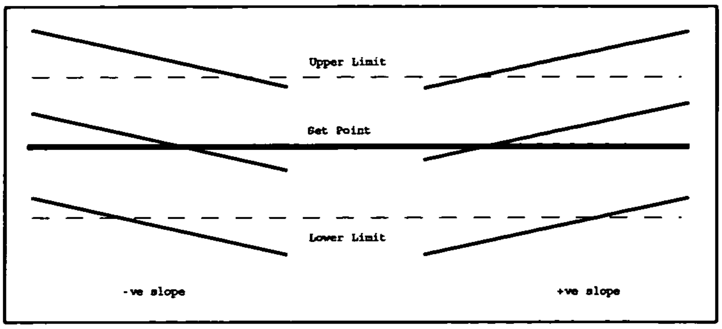

Figure 3. Trend versus Process Limits.

Theoretically, the paste weight in the weigh hopper prior to the press mould should be the same as the weight of the anode pressed from said paste. Any major difference between these two weights indicates a problem either with the weigh hopper sensor or with the anode weight sensor. Furthermore, there is a direct relationship between the anode height, the anode weight and the hopper weight. As the hopper weight increases, so should the anode weight and anode height. The mean value of the Green Apparent Density (GAD) in relation to its set point provides an additional check on a sensor reading. Thus, a truth table, shown in Figure 4, can be compiled comparing trends of these variables in order to arrive at possible sensor or set point problems.

GAD	*Anode Trend Slopes*			Delta Weight*	Problem
	Anode Weight	Hopper Weight	Anode Height		
OK	+'ve	+'ve	+'ve		Hopper weight set point
	-'ve	-'ve	-'ve		Hopper weight set point
	+'ve	-'ve	+'ve		Hopper weight sensor
	-'ve	+'ve	+'ve		Anode weight sensor
	+'ve	+'ve	-'ve	<limit	Anode height sensor
	+'ve	+'ve	-'ve	>limit	Height and hopper weight sensors
	-'ve	-'ve	+'ve	<limit	Anode height sensor
	-'ve	-'ve	+'ve	>limit	Height and hopper weight sensors
	+'ve	-'ve	-'ve		Anode weight sensor
	-'ve	+'ve	-'ve		Hopper weight sensor
Low				<limit	Anode height sensor reading high
				>limit	Anode weight sensor reading low
High				<limit	Anode height sensor reading low
				>limit	Anode weight sensor reading high

* Delta weight = process limit for anode weight minus hopper weight

Figure 4. Truth table for anode sensor problems.

5.2 Mixer Paste Temperature Problems

The temperature of the paste entering the press mould has to be maintained within tight limits, else the anode will collapse or break up during conveyor transfer. Thus, the temperature in the mixer must be closely monitored and controlled.

Some of the reasons for paste temperature in a mixer being high are:

- Proportional heat transfer oil (HTO) flow valve on mixer stuck;
- Mixer HTO outlet temperature set point > HTO temperature set point.
- A mixer HTO outlet valve stuck fully open;
- HTO outlet temperature too high;
- System in HOLD-UP mode, ie discharge conveyor stopped and all proportional HTO flow valves shut.

Some of the reasons for paste temperature in a mixer being low in a mixer are:

- Proportional HTO flow valve on that mixer stuck;
- HTO outlet temperature too low;
- HTO pump not running;
- Coke drier not working;
- Vent (to extract dust or pitch fumes when charging) to vacuum system stuck open.

5.3 Press Paste Temperature Problems

Some of the reasons for the temperature of the paste entering the press mould being high are:

- Paste from mixer too hot;
- Paste cooling spray pump not running;
- Fan providing air cooling not running;
- Water spray air pressure low;
- No water flow to sprays;
- Spray head blocked or damaged.

5.4 Ball Mill Problems

Some of the ball mill problems, causes and their solutions are outlined below:

Problem	Cause	Solution
• Blaine Index > 2400	Product too fine	Open damper a notch
• Blaine Index < 2000	Product too coarse	Close damper a notch
• Motor amps & feed rate drops	Ball mill underfull	Increase feed
• Motor amps & product rate drops, feed rate OK	Ball mill overfull	Decrease feed
• Feed rate and product rate drops	Feed bin empty	Check status of equipment
upstream		

6. EXPERT SYSTEM DEVELOPMENT

6.1 Software and Hardware

The problem definition called for a facility to have a means of editing and applying sets of rules together with peripheral tools such as interface facilities for holding conversations with databases and control systems, kits for using external programs and language calls, graphics and debugging aids. Lacking extensive programming skills, it was decided to a proprietary software package that would provide all the required facilities in a single software shell.

While there are several packages available, *Level5 Object* was chosen on the grounds of prior use by the writers and client, it being relatively inexpensive and its incorporation of all of the required facilities, namely, a forward and backward chaining rule base facility with editing and debugging functions, ODBC and DDE links, a toolkit for writing to external programs, ability to read and write to text files, charting and hypertext functions.

The first year of development was carried out on realistic, but non-live data, on a stand-alone 486 PC with 8 Mb of RAM in Windows 3.1. Currently, further development is being carried out on a PC with Windows NT connected to the Plant's network by modem. The NT environment is required because of the number of applications running at the same time, ie the main *Level5* application holding conversations with Excel and Access files with the Excel file itself holding a conversation through the NIF server with SCADA, and to maintain security when accessing over the network.

6.2 Knowledge Base

The knowledge base formally sets out rules derived from the truth table shown in Figures 3 and 4 and derived from the problems defined in Section 5.

Some of the key rules are given below.

Rule 1: IF GAD trend OK
AND Anode weight trend positive
AND Hopper weight trend positive
AND Anode height trend positive
THEN Problem with the hopper weight set point

Rule 2: IF GAD trend OK
AND Anode weight trend positive
AND Hopper weight trend negative
AND Anode height trend positive
THEN Problem with the hopper weight sensor

Rule 3: IF GAD trend OK
AND Anode weight trend negative
AND Hopper weight trend positive
AND Anode height trend positive
THEN Problem with the anode weight sensor

:

Rule 8: IF GAD trend Low
AND Anode weight minus hopper weight < process limit
THEN Anode height sensor is reading high

:

Rule 10: IF GAD trend High
AND Anode weight minus hopper weight < process limit
THEN Anode height sensor is reading low

⋮

Rule 16: IF paste temperature in Mixer #1 is LOW
AND HTO Pump is not running
THEN Problem is HTO pump is not running

⋮

Rule 22: IF Paste temperature in Press is HIGH
AND water spray pump is not running
THEN Problem is water spray pump is not running

⋮

Rule 32: IF BM feed rate below 10
AND product rate below 8
THEN Problem is BM feed bin is empty

6.3 Testing

Development has been predominantly carried out on realistic, but non-live data. Periodically, the application was run on the plant network on live data, accessing the SCADA database and NIF server. Thus, the rule base was modified to deal with real data and modified in line with user requirements. The application was developed to properly hold conversations with databases, SCADA and plant control systems over the network. The latter exposed many problems not obvious on a stand-alone PC.

Testing was carried out by running the application continuously through many cycles till failure, where a cycle in test mode took four minutes. While some failures were caused by faulty programming, which were fixed, others were caused by shortcomings in the *Level5 Five* software, which were worked around. The software problems manifested themselves as losing the ability to plot a chart or part of a chart, to the displaying of a fault message with the subsequent shutting down of the application. This aspect of testing proved to be very time consuming, but with work arounds, reliability improved from a mean time between failures of 10 minutes to 200 hours. The software suppliers have identified the problem as memory leakage and will be releasing a new version to correct this problem this year.

On the human side, problems were experienced with the changing of the client's personnel resulting in changes to the project specification, especially in the way process statistics was to be presented.

The developed system, now running on live data, is providing an accurate diagnosis of plant problems such as sensor drift, sensors and instruments needing re-calibration, the ball mill requiring make-up of balls and mechanical damage to the ball mill. While the system has not yet been installed for general use by the operator, its use in the development phase has led to the realisation of the need to replace the sensors with a more reliable unit.

7. CONCLUSION

An expert system has been developed to monitor and optimise a complex process of anode production in an aluminium plant. The expert system interacts with the SCADA system in real-time, applies rules from the knowledge base and advises on how to optimise the production process in order to obtain anodes of a consistent and high quality.

The research has demonstrated the feasibility of using an expert system based software system to oversee a complex production process, to analyse large amounts of data and to provide meaningful and timely information to the operator to enable the operator to take any necessary corrective action required.

While *Level5 Object* is a useful development tool and probably adequate for one-off type enquiries, there is a big question mark as to its robustness to continuously monitor a process. If the problems and shortcomings experienced with the current package are not resolved by the next release of this product, then it may be necessary to hard code the application, re-write it in Visual Basic or transfer it to a more powerful shell such as G2 for use in the production environment.

8. ACKNOWLEDGMENTS

This research was funded under a grant from Comalco Aluminium (Bell Bay) Ltd., Tasmania.

The authors are grateful for the help provided by process specialists at Comalco, namely, P.W. Sulzberger, M. Hughes and S. Hancock.

9. REFERENCES

IEA/AIE (1992) *5th. International Conference,* Villa L., Sierra C., Martine A.B. and Climent J., *Intelligent Process Control by Means of Expert Systems and Machine Vision*

Mavrovouniotis M.L. (1990), *Artificial Intelligence in Process Engineering*, (San Diego: Academic Press), Myers D.R., Davis J.F. and Hurley II C.H. *An Expert System for Diagnosis of a Sequential, PLC-Controlled Operation.*

Payne E.C. and McArthur R.C. (1990) *Developing Expert Systems*, (New York: John Wiley & Sons.

Pham D.T. (1988) *Expert Systems in Engineering,* Taunton J.C. and Haspel D.W. *The Application of Expert System Techniques in On-Line Process Control.*

APPENDIX 6

Project Sponsor's Review

COMALCO

COMALCO SMELTING

BUSINESS UNIT SYSTEMS GROUP

Terrace Office Park, Level 3, Building 2, 527 Gregory Terrace, Bowen Hills, Queensland 4006

File No: J:\OFFSERV\TYPING97\IFARRAND\IF003.DOC

5 March 1997

Dr Michael Negnevitsky
Department of Electrical &
Electronic Engineering
University of Tasmania
GPO Box 252C
Hobart
TASMANIA 7001

Dear Michael

Summary

The Anode optimisation project has finished and this letter is a summary of the results. The project was undertaken by Paul Gale from the University of Tasmania as part of his Masters Degree. The focus of the project was to investigate the opportunities of presenting to the operators information about the process and guidance to correct problems. The project demonstrated that it was possible to provide information that integrated historical data, current status, predicted trends, and SQC data into one package. It also checks for inconsistent data when viewing the process as a whole. Further more it provided guidance to the operators about possible actions. This system runs continuously, scanning the database and SCADA system generating charts, warnings and advise to the operators.

Achievements

The system provided the operators with:

- Early warning that there was a problem with instrumentation. The existing SCADA system can in some cases detect total failure but the new system provides warnings about drift in calibrations.
- SQC charts about critical processes. The SCADA system could only provide run charts.
- Predictions when processes where going to exceed their limits in sufficient time for the operators to fix the problem.
- Integrated data across several processes looking for inconsistencies.
- Some possible actions they could perform to fix the problem, by integrating the above data with some simple rules.

History

The project initially researched the opportunities available in the entire Carbon Plant. Early on it was decided that the scope would be limited to proving concepts rather than provide a final working solution. An expert system (LEVEL 5) was used to write the system. This enabled rules to be checked without large amounts of code.

The Green Carbon Plant was chosen as a trial area as this was a source of variation in anode quality. Specifically the press area was targeted. The project then worked upstream to the mixers and crushers.

In the press area data was being gathered for part of the technical system. The data quality was questionable due to drift in the instrumentation calibrations. This limited the potential of the technical system and also was a source of process variation which has a large impact in anode density. It was found that by analysing the last hours data for the green anodes from the database and integrating this with the current data from the SCADA system useful information could be generated.

The concepts of prediction, and SQC charts were added later after consulting the statistician working in the area.

Limitations

The LEVEL 5 package that was used to implement the system has proved to be unreliable. Before this system was turned into a production system it would be necessary to re-code the concepts using a more stable package such as C++. As a prototyping tool the original package was suitable because of its flexibility.

The application is slow and if the scope of the application was to be widened then this too would also force re-coding.

Limited acceptance by the operators because the package kept on failing after running for severalhours.

Future

The system provided it is rewritten could help reduce variation in the Green Anode Plant by:

- monitoring critical functions and instruments,
- provide early waring of problems and,
- provide consistent advice to operators.
- By monitoring upstream process it could advise changes in down stream process setting to minimise the effect of detected variation in the upstream process. This is beyond the capability of the current process control systems.

Yours faithfully

Martin Hughes
Specialist Systems Analyst

cc
Bob Still
Ian Farrands
Sam McNeill
Alan Bothe
Paul Gale